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April 15, 1981

OSP #87407

National Science Foundation
Central Processing Section
1800 G. Street
Washington, D.C. 20550

Attn: Dr. Richard Isaacson

Re: Renewal Proposal for Grant No.PHY-8109581

To whom it may concern:

Massachusetts Institute of Technology submits herewith ten(10) copies of the above-referenced renewal proposal entitled "Interferometric Broad Band Gravitational Antenna" to be performed under the supervision of Professor Rainer Weiss of M.I.T.'s Department of Physics.

This proposal is submitted for the period June 1, 1981 through May 31, 1984 at a total estimated cost of $1,282,600, with an annual estimated breakdown as follows:

First Year:	$337,719
Second Year:	$467,509
Third Year:	$477,382

If you have any further questions, please do not hesitate to contact the undersigned at the above-referenced number.

Sincerely,

Maureen Kelleher

Maureen Kelleher
Assistant Director

MK/pav
ENCLOSURES
cc: Prof.R.Weiss
D.Gould

NOTICE OF RESEARCH PROJECT

SCIENCE INFORMATION EXCHANGE

SMITHSONIAN INSTITUTION

NATIONAL SCIENCE FOUNDATION

PROJECT SUMMARY

SIE PROJECT NO.

NSF AWARD NO.

FOR NSF USE ONLY

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

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

Massachusetts Institute of Technology

DDRESS (INCLUDE DEPARTMENT)

Department of Physics
77 Massachusetts Avenue
Cambridge, MA 02139

RINCIPAL INVESTIGATOR(S)

Rainer Weiss, Principal Investigator; Paul S. Linsay, Co-Investigator

TITLE OF PROJECT

"Interferometric Broad Band Gravitational Antenna"

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

We are continuing the development of a prototype laser interferometric gravitational antenna, and will begin a study of the design of a large antenna (10 km arms) that will be capable of measuring astrophysically interesting sources. Antennas of this type are based on ranging between virtually free masses that follow the time-dependent gravitational strains in a gravitational wave. This type of antenna is broadband, sensitive to differential excitation of tensor gravitational wave polarization, and can be extended to baselines comparable to the gravitational wavelength. Being broadband, antennas of this style can detect periodic and transient sources and can be used as gravitational radiation radiometers to measure the spectral density of incoherent gravitational wave noise.

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ABSTRACT

We propose to continue the development of a prototype laser interferometric gravitational antenna, and to begin a study for the design of a large antenna (10 km arms) that will be capable of measuring astrophysically interesting sources. Antennas of this type are based on ranging between virtually free masses that follow the time-dependent gravitational strains in gravitational wave. This type of antenna is broadband, sensitive to differential excitation of tensor gravitational wave polarization, and can be extended to baselines comparable to the gravitational wavelength. Being broadband, antennas of this style can detect periodic and transient sources, and be used as gravitational radiation radiometers to measure the spectral density of incoherent gravitational wave noise. In addition, we will continue research into active isolation stages.

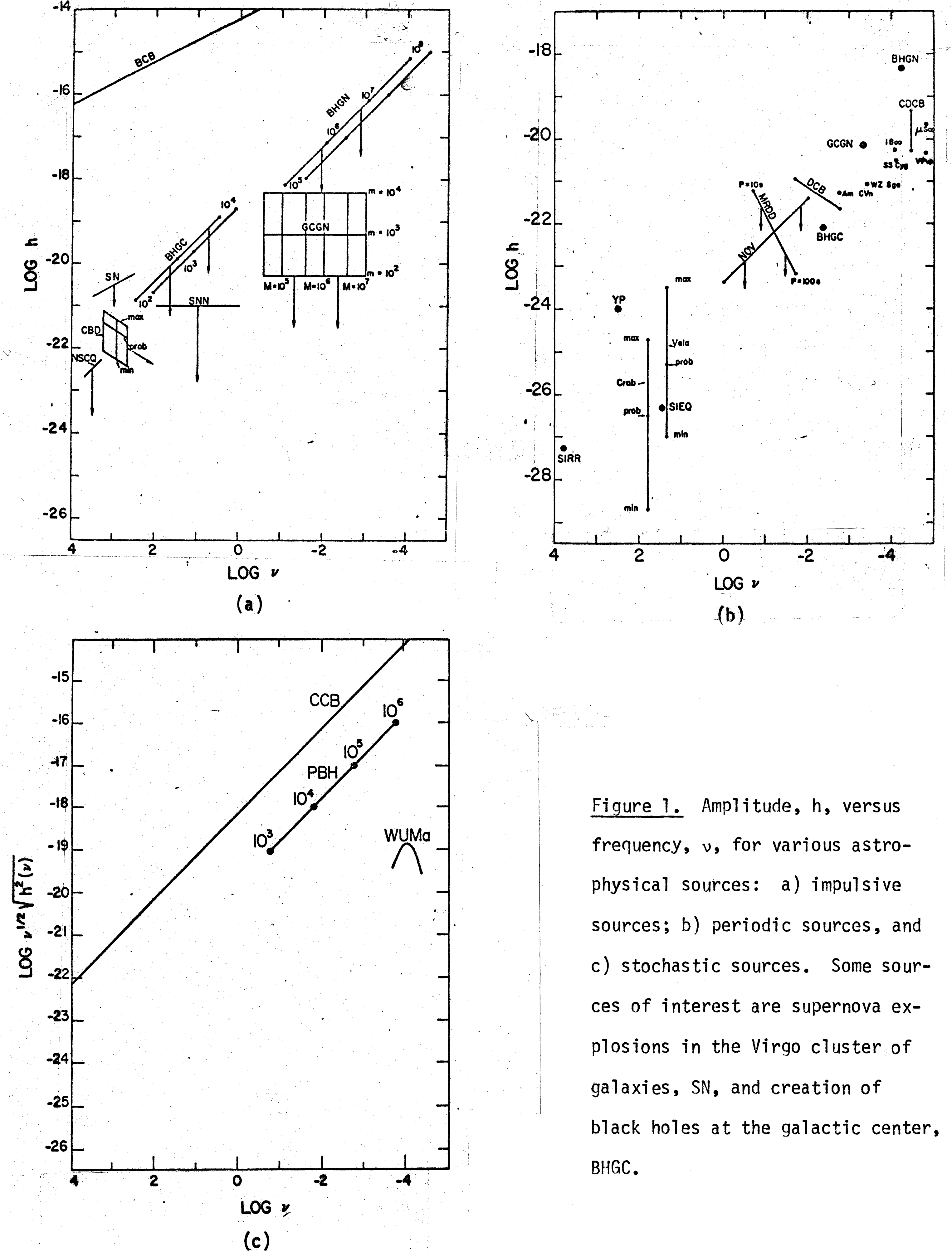
The purpose of the prototype antenna is to understand the noise sources in the system, and to understand the validity of the noise models. The active isolation stage currently works in one dimension, and will be extended to two, and possibly three, dimensions, in order to understand the problems that arise from cross-coupling between modes. This type of stage will be important in the construction of a large antenna.

Parallel to this work, we would like to begin studying the design and construction of a large scale (10 km) interferometric gravity antenna. The study will address the engineering, construction problems, and costs of a large system. We expect that this study will take roughly three years to complete.

PROPOSAL OF RESEARCH

The scientific rationale for the research we propose has not changed in the past year. It is to ultimately detect or set astrophysically interesting limits to the gravitational radiation flux incident on the Earth. No discoveries in the recent past have made the aim of this research less compelling. Indeed, the continued advance in both theoretical understanding of ultradense relativistic matter in the universe, as well as the accumulating evidence that there are strange things afoot in galactic nuclei (including ours), objects moving near limiting speed, and relativistic mechanisms in double radio sources, all are making the concept of gravitational astronomy as a probe to these processes a more urgent and timely research field. We will even go so far as to say that at MIT there is an awakening and more optimism for the success of such an effort.

A good place to begin is with the now familiar Figs. 1 and 2, which show the best estimates and upper limits (in 1978) of the astrophysical gravitational radiation spectrum for three classes of gravitational radiation sources -- impulsive, periodic, and a stochastic background. The estimates, poor as they may be, have not changed substantially since this compilation. Associated with these estimates are the anticipated performance (again made in 1978) for different types of antenna systems. There is no new information which changes the estimates materially. Cooled acoustic antennas-- the Stanford experiment in particular -- have come to perform as expected. Electromagnetically coupled antennas have also progressed, not quite to the limit allowed for by their length. The Munich group has managed to make an interferometer perform to within a factor of 3 of the shot noise limit in a multi-pass system using Herriott delay lines. There

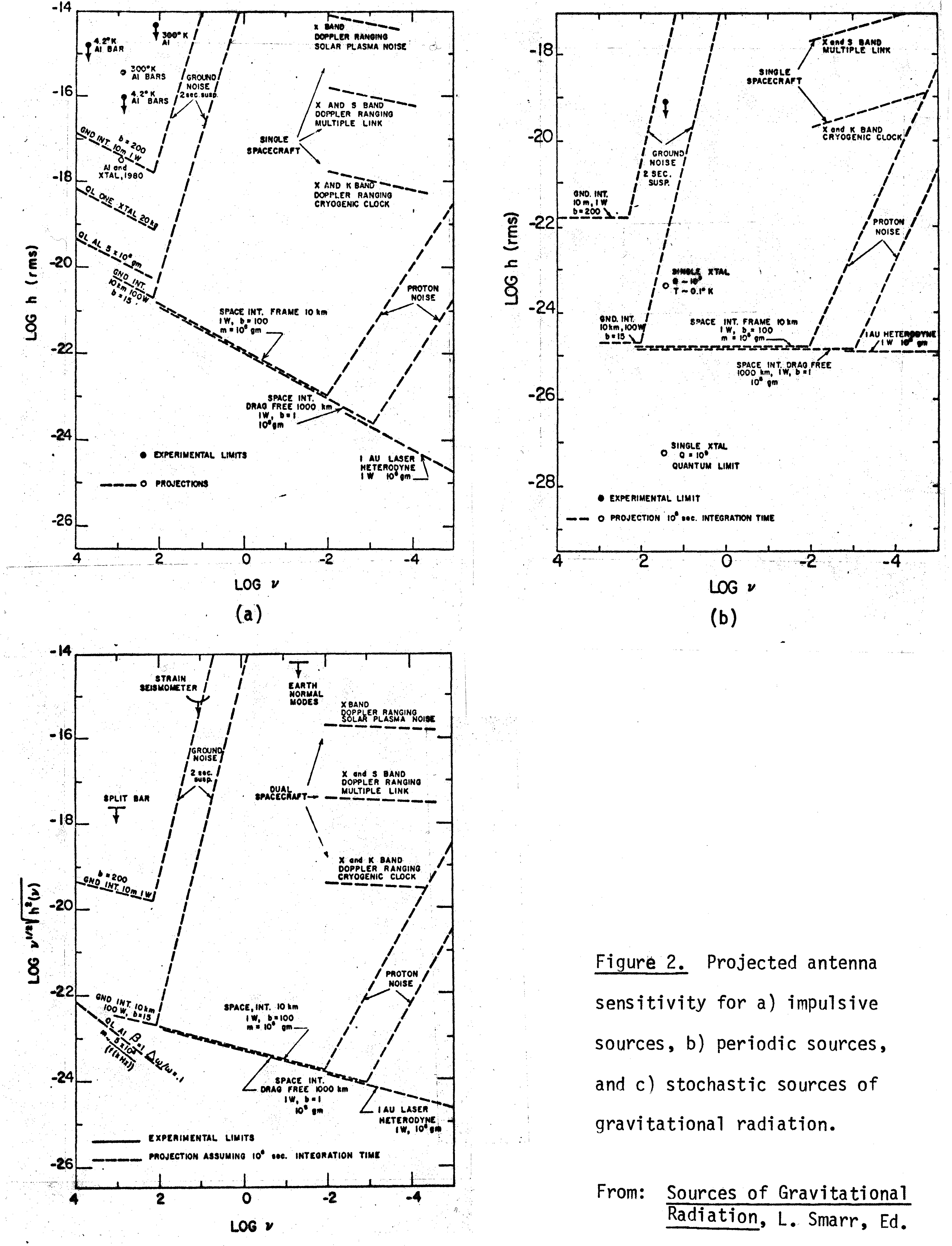


(a)

(b)

(c)

Figure 1. Amplitude, h, versus frequency, ν, for various astrophysical sources: a) impulsive sources; b) periodic sources, and c) stochastic sources. Some sources of interest are supernova explosions in the Virgo cluster of galaxies, SN, and creation of black holes at the galactic center, BHGC.



(a)

(b)

(c)

Figure 2. Projected antenna sensitivity for a) impulsive sources, b) periodic sources, and c) stochastic sources of gravitational radiation.

From: Sources of Gravitational Radiation, L. Smarr, Ed.

have been advances in the understanding of the ultimate limits of these electromagnetically coupled systems through the work of Carlton Caves at Cal Tech. The quantum limit is not a sharp barrier for these antennas at high frequencies. Caves' rigorous calculations support the more heuristic ones carried out beforehand. The optimal optical system, whether it be the multi-pass delay lines (MIT and Munich) or the differential Fabry-Perot (Glasgow and Cal Tech) is not yet determined and, as we will try to show, may not be the important concern in the development of such an antenna designed to measure interesting astrophysical limits. One thing that has changed is the estimate of the ground noise limit, assumed in Fig. 2. This estimate may be too pessimistic, as inertial stabilization schemes can be made and demonstrated that are better than the 1978 projections. Furthermore, the fluctuating terrestrial gravitational gradient also may not impose as hard a limit as previously supposed, if one is clever with the antenna configuration.

The major change at MIT is in the conception of how the project is to proceed. We have come to the realization that it is now time to begin studying the design and construction of a large scale (10 km) interferometric gravity antenna. This study will run parallel to the work on the prototype antenna, and address the engineering and construction problems and costs of a large system. We expect that this study will take roughly three years to complete. If the results of the study are favorable, we would like to begin construction of the large antenna.

The impetus for developing electromagnetically coupled antennas has always been that they offer the ability to make broadband measurements of the gravitational radiation spectrum, and would be able to measure all three classes of gravitational radiation sources. More important, although not as much work has been done on their demonstration in small prototypes as on the acoustic antennas, the problems that must be solved to achieve interesting sensitivities are primarily ones of scaling rather than of developing fundamentally new and difficult technologies. One can say this in a very bold way. It is now, and has been for several years, <u>entirely in our capability</u> to construct a gravitational wave antenna with an interesting sensitivity, $\Delta\ell/\ell \sim 10^{-21}$ at one kHz, if only one was willing to spend the large amount of money involved. There would be no subtlety in such a system, and precious little application of the new technologies that we are working on in the laboratory prototypes at MIT and elsewhere.

<u>We are not proposing the following</u>, but imagine such a system: a square 100 km on a side, constructed of thick wall stainless steel tubing 42" in diameter, including the diagonals. The system is buried 200 meters at its midpoint to accomodate the curvature of the Earth. There are 400 miles of tubing in such a configuration. The tubing is supported every ten meters on servo mounted cradles. The system is evacuated to 10^{-7} mm using 10^5 ion pumps. The system includes 6 interferometers encompassing all pairs of adjacent differences. The optics are single beam interferometers using retroreflectors. All interferometers are servoed to the white light fringe by electrooptic and electrical and mechanical controllers. The light sources

are 60 ion lasers each delivering 20 watts multi-mode. Each interferometer is modulating 100 watts. The tubing is blackened with Martin Marietta black and baffling. Each end station, six in all, has a volume of three cubic meters held at 10^{-8} mm. Each vacuum system is itself supported on a 100 ton 3-dimensional active isolation system. Each end station is internally magnetically shielded to one milligauss by active and passive shields. The data rate is close to 1 megabit/sec to sample to several kHz. In order to correlate the data from the different interferometer arms to make the gravity gradient regression analysis, several multiplications per microsecond are required.

Such a system would have the required sensitivity at 100-1000 Hz; more subtlety, especially in the antenna supports, would be required to stretch the response to lower frequencies. The point made by the above presentation is the following: Look at the requirements individually. They are all within our present technical capability, even in a commercial setting. However, the cost of such an installation ranges between 150 and 200 million dollars, a major U.S. investment in science rivalling medium size space missions and probably too large, considering the limited applicability of such an installation to one branch of science, even though the rationale for such an installation could embrace earth science and other relativity experiments, in fact might even have a military application.

The realization that such a system is possible, but outside the range of economic reality, does color and affect in a deep way the best strategy for pressing the present effort. If one follows the natural desire to see the field come to fruition in a timely manner, it would drive a commitment to the idea, and suggest a strategy to analyze the individual cost factors and optimize the antenna as a system. This may sound like administrative-ese, but it is in fact the core of this proposal. In plain English, what are the areas to work on to bring the cost of such an installation down by a factor of 10 to 20? This last statement has to be interpreted in a broad sense. There are elements on all levels, some of which will be described shortly. There are strictly handbook-type engineering problems -- optimization of tube wall thickness versus the number of supports, for example. Other classes of problems which one may classify as engineering - experimental problems -- for example, can one get away with standard schedule tubing with the vacuum required, or how does one optimize the number of pumps or the style of pumps. There are subtle engineering problems, with difficult trade-offs -- the complexity of the optical system, for example, whether to use multi-pass or single-pass, versus the tubing diameter and antenna length. And finally, some demonstration experiments of items that could really produce major cost savings, but which have novel and risky engineering solutions.

If one takes a broader view, and looks at the antenna project as an entire system (which we have not done up to now), it will inevitably turn out that the order of priorities of the important demonstration experiments will change. The approach we have all been taking, of beginning small and demonstrating the performance of small prototype systems to their theoretical limits, may not be sensible. The small systems, of course, have some of the ingredients of the larger system, but their problems may not be the problems of the larger system. A good example is the backscattering problem on the mirrors, which could be a decisive problem in a small interferometer, and of far less consequence in a larger one, whereas the optimization of the optical beam size may very well be the overriding concern in the large system. Another example is the work of superb ground noise isolation systems, which are interesting in their own right, but may be inappropriate if the cost of the isolation system is more than the cost of extending the antenna to achieve the same strain signal to noise.

Our proposal is multi-faceted. Clearly, we will continue with the development and analysis of our 1.5 meter prototype system in the laboratory. Too much time has been invested in it not to see it to completion. There is still much to be learned from it, particularly to show where the noise modeling works and where it fails. Furthermore, it is also extremely satisfying to have a piece of equipment to try ideas on. We will continue to expand our research into active isolation stages, which are both showing promise and will be important in any larger installation. We will not strive to build an intermediate antenna. This is being carried out at Glasgow and Cal Tech, and possibly in Munich. On the other hand, we do propose to begin, in a concerted way, the engineering study of a larger system, with the intent to build such a system. We are interested in getting a real understanding of the cost trade-offs, and where necessary, as driven by the study, to carry out side and pilot experiments on technically relevant cost-savings items. A systems study cannot be carried out by our group alone, nor would it be appropriate. We therefore propose to subcontract some of the work to industry, even at this early phase.

In preparation for this, we have begun informal negotiations with the scientific and engineering consulting firm of Arthur D. Little in Cambridge, MA, and with the engineering firm of Stone & Webster in Boston. We presented both companies with an outline of the experiment, using a 10 km version of the antenna as an example for discussion. The preliminary mechanism of the interaction is that we propose, for heuristic purposes, a specific set of problems which we have identified within the framework of an example design described by us. Such a study must focus on a strawman design based on our initial instincts of what is needed. These preconceptions are bound to change in the course of the study. We hope to maintain flexibility by establishing cost scaling laws at each technical branchpoint. However, to get anything meaningful from such a study, we must begin with a specific example.

We have categorized the study in the following manner:

Configuration Study - Within the constraint that the longest path be 10 km, what is the optimal geometry to permit regression of local time varying gravity gradients, as well as to be sensitive to both polarizations of the gravitational radiation field? This study encompasses estimates of the gravity gradient noise spectral density due to atmospheric density fluctuations, water table fluctuations, gravity gradient noise from longitudinal seismic disturbances, incidental noise from birds, airplanes, and other anthropogenic sources, the gravity gradient signals of low flying satellites, and possibly the military application of detecting these. This study is best done by MIT directly; however, a member of the A.D. Little group has shown interest in this as well.

Site Selection - Considerations are the seismisity of the site, in particular the existence of local shear, the availability of the land, environmental impact, corrosion caused by the specific location, and most important, the ease of working with the terrain for trenching or framing, and the proximity to sources of supply for developing the site. Again, to prevent the study from being too open-ended, specific suggestions of available sites are to be studied first. Land around the Sandia Corporation of Albuquerque, New Mexico, both in Albuquerque, as well as a plot in Nevada, now abandoned, but developed by Sandia for the Nuclear Weapons Testing Program, will be considered. The connection to Sandia is worth cultivating, as there is an active geophysical research group there who, in the early 1970's, assembled a 1.6 km long laser strain seismometer patterned after the design of Jon Berger of the University of California at San Diego. Incidentally, this installation cost $100,000. The other site to explore is in the Plain of St. Augustin, at the location of the Very Large Array (VLA). Both A.D. Little and Stone & Webster would be interested in pressing such a study.

Professor Nafi Toksoz, of the Earth and Planetary Sciences Department at MIT, will join us in the study of site selection and configuration. His interest in the study lies in its potential application as a means of measuring two-dimensional earth strain over large enough base lines to sample non-local structural deformations, especially as they relate to tectonic activity. Large laser interferometers are probably not competitive with the promise of VLBI in measuring tectonic plate movement on the scale of thousands of kilometers. However, VLBI most likely will not measure on the 10-100 km scale, and furthermore, a large laser system can go part of the way to act as groundproof for the VLBI measurements.

The remaining categories are not orthogonal, but indeed, highly interactive, in both an engineering sense and in their effect on cost optimization.

Optics - The optical design is one of the most difficult aspects of the engineering problem, and consequently the one most likely to benefit from ingenuity. It is clear there are many trade-offs in the optics; ingredients in the formulation of the problem are: available light power, the degree of multipass, pointing precision, beam diameter, light storage time, and the gravitational frequency response of the antenna, to mention a few. There is, however, an overriding principle. The optics plays the role of the differential displacement transducer in these antennas. When the transducer noise matches the other noise sources in the system -- the stochastic noise forces on the antenna end points -- there is clearly no point in making the transducer better until the local noise sources can be reduced further. The major attribute of the electromagnetically coupled antenna lies in the fact that they can be extended to lengths close to the gravitational wavelength. Many of the stochastic forces are due to local phenomena -- the ground noise, thermal noise, electric and magnetic forces -- which do not grow with length. If these were the only noise terms, one would achieve a linear increase in amplitude signal to noise for gravity detection with length. There are noise terms that grow with the length. The two we have identified are: (1) Propagation noise, index fluctuation in the vacuum, which should scale as $\ell^{\frac{1}{2}}$, but could be made negligible with a sufficiently good vacuum, 10^{-6} mm Hg in a 10 km length. (2) Time dependent gravity gradient noise, which in a naive calculation grows linearly with the length. However, depending on its power spectrum and origin, the local gravity gradient noise could be discriminated from the gravitational radiation from distant sources by using the local time varying gravitational potential's third derivatives. This aspect of the antenna design (already mentioned under Configuration) is one of the more interesting scientific-technical studies proposed, and may have more impact on the design and configuration of a large antenna system than any other, as it affects the low frequency performance of the system.

The rationale for having written the above paragraph, much of which is already known by all who have been working in this area, highlights the fact that the optical design cannot be viewed in isolation from the rest of the system. The fact that we, or any other group, may demonstrate shot noise limited performance in a specific configuration certainly adds credibility to the antenna concept, but may not be the overriding concern in the practical antenna. As a hypothetical example, suppose it turns out that the only way to beat the stochastic noise forces is to make large structures. Then much of the effort now expended by all of us to make multi-pass systems, with their very special problems, work, may be misdirected. What we should be working on are refined beam steering techniques, feedback techniques to keep the tubes straight, and beam diameter minimization.

As the basis of the optical study, we are considering the following options: Multi-pass reentrant delay lines, non-reentrant delay lines (corners and beam translation) to the limit of a single beam, and Fabry-Perot cavities. We will not study fiber optics, or adaptive optics, which some have suggested to us as a technique to eliminate the need for the evacuated light paths.

At the outset, one already knows some of the advantages and limitations of these designs. The multi-pass delay lines may experience difficulty with multiple backscattering of the beam, first analyzed by Ron Drever. The temporal separation of the beams grows with antenna length, and this problem, if it exists, becomes more easily soluble by light beam frequency and phase modulation at some expense in duty cycle. Another more serious difficulty with multi-pass dealy lines of both reentrant and non-reentrant type is that the tube diameter is not minimized. A Gaussian beam is the minimum width beam possible.

It scales in maximum diameter at 1/e as $(8\lambda\ell/\pi)^{\frac{1}{2}}$, for example, 4.5" in a 10 km length, for a wavelength λ = 5145Å. Since the delay line multi-pass systems rely on spatial separation of the beams, the total envelope dimension must scale at least as the square root of the number of beams. For a 10 km system, with ten beams, the tubing diameter must then be larger, by a factor of 3-4, than for a single beam. The delay lines do have the significant attribute that their properties are independent of wavelength, which permits their use with frequency unstabilized high power laser sources, when operated in an interferometer near the white light fringe.

The Fabry-Perot cavity has the advantage of having the minimum beam diameter, and probably less difficulty with mirror scattering, important in small length, high finesse systems. It imposes a constraint on the frequency width of the light source, and therefore on the maximum useable power.

Problems associated with precision beam steering, laser angular jitter, and the effects of beam apodization by the tubes are common to all the optical schemes. In thinking about these problems, several side experiments are suggested. An experimental study of the phase shift of a Gaussian beam on axis, when apodized by absorbing and baffled tubes at the beam edge, must be undertaken. Another feasibility experiment would be the engineering implementation of an active deformable mirror to steer and mode-match a light beam into a long light path. The mirrors used in the large structures would be virtually flat. Their slight curvature and the directions of their normals would have to be under servo control by beam monitors stationed along the path, or at the ends.

An unattractive option, due to its complexity, but one that must be considered, as it may lead to a substantial cost saving if tubing diameter is the real cost driver, is the use of internal relay optics. The tube diameter would scale inversely as the square root of the number of internal elements for a fixed beam length. It is important to evaluate the headaches associated with alignment and the new sources of acoustic and seismic coupling, as well as losses in the optics, which may yet prove to outweigh the cost savings in tubing.

Another problem closely related to the optical configuration is the present availability of commercial high power visible lasers. At present, the most powerful optical lasers are the rare gas ion lasers manufactured by Spectra Physics and Coherent Radiation. They develop on the order of 20 watts multi-line and several watts in a single line (Argon 5145Å, approximately 3 watts). Several years ago, the possibility of isotope separation using visible lasers drove a development in the industry toward more powerful lasers. At this time, due to technology shifts in the isotope separation program, this development program has ended.

There is no fundamental scientific challenge in constructing more powerful argon lasers. Rumor has it that the Russians at Novo Sibirsk have assembled a 500 watt laser. But there are substantial manufacturing and engineering problems. Spectra Physics marketed a 40 watt laser by using the expedient of putting two of their 20 watt lasers in series. It did not turn out to be a very successful product. To get more powerful lasers will require redesign of the plasma tubes to achieve both higher total current as well as a larger current density. There are designs for such tubes, but no commercial applications to drive the development. At present, if one wants to have 100 watts of visible cw laser power, the only way is to use lasers in parallel (PL has suggested this), or to develop the technology of a high power laser in a university or government laboratory. We are not privy to military developments. The choice of moving to longer wavelengths, in particular 10 µm, the operating wavelength of the CO_2 laser, could be considered, but we will not do this in the initial study.

Arthur D. Little has shown interest in carrying out engineering studies of some of the optical problems. At MIT, a great deal of the time in the next year will be devoted to these. We will be joined by Professor Shaoul Ezekiel of the Electrical Engineering Department and the Aeronautical Engineering Department at MIT in this aspect of the project. He has a scientific interest of his own in the large structures as a means of developing a Sagnac interferometer system (passive laser gyro) for studies of torsional earth motion, and the preferred frame tests that could be performed with meaningful sensitivities in structures of the size envisaged.

Seismic and Acoustic Isolation - The design and testing of seismic and acoustic isolation systems fall squarely in the category of subtle engineering problems. At present, there exist no commercially available isolation systems that match the requirements of a broadband electromagnetically coupled gravitational antenna operating at astrophysically interesting sensitivities. It is possible, as has been demonstrated in the research on acoustic antennas, to isolate ground and acoustic noise to acceptable limits at frequencies above several hundred Hertz in a narrow band. This has been done with passive mechanical filters in a completely analogous way to the design of electrical filters using lumped circuit elements guided by well known filter synthesis theory. The same techniques could be applied to the supports of an electromagnetically coupled antenna if all that were desired were gravity wave detection in a narrow frequency band. The promise of these antennas, however, lies in their broad bandwidth and potential in detecting low frequency ($f < 100$ Hz) gravitational radiation. To make good on this promise poses a challenge in the design of isolation systems.

The approach we have taken is to use active isolation by incorporating a seismic reference element in a closed servo loop. The technique, described in Appendix 1, is quite successful, as demonstrated in a one-dimensional system. Work on these systems will continue at MIT in the next year to extend the concept to three dimensions, as well as to improve the isolation to its theoretical limits determined by the seismic reference element noise.

Construction Strategy - The optical and vibration isolation systems are decisive in the design; however, they must be considered in context with other elements which fit broadly in the category of construction strategy. Among these are the choice of tubing, tubing installation and support, alignment, thermal control, and vacuum. These elements are highly interactive in a cost trade-off analysis.

Although no system has ever been constructed that is exactly like a large electromagnetically coupled antenna, there is experience with some of the aspects of this construction in other projects. The following are examples. Construction techniques and maintenance procedures for long lines of tubing have been developed by the gas utilities. Some of the problems in thermal control and alignment of long tubes have been studied and solved in the construction of the microwave waveguide linking antennas of the VLA. Alignment and vacuum specifications comparable to or better than those needed in a large electromagnetically coupled antenna are encountered in linear particle accelerators. It would serve the study well to begin by using these examples, where appropriate, as a baseline for establishing and scaling costs.

The experiences of the gas utility companies is both interesting and useful, as it uncovers cost factors we might not have thought of. The gas companies use standard schedule carbon tubing ranging in diameter from 42" in major lines to 10" in branch lines. The tubing has to sustain a gas pressure of 1000 psi. The tubing is coated to prevent corrosion, joined by arc welding, and buried in trenches so as to allow 30" of backfill. The tubing is supported by sand, and occasionally by gravel, if drainage is needed. The design lifetime of the gaslines is 30 years. A typical total cost of laying 24" diameter pipe is $450,000 per mile. The tubing cost is approximately one-third of the total, the trenching, welding and backfilling costs are approximately one-half. The remaining costs are in surveying, coating, testing, and inspection. A typical overall construction rate is a mile per day.

Gas lines are not high vacuum systems , nor do they need to be aligned to a one-tenth of a second of arc over 10 km, as would be required in an antenna, but many of the procedures used in their construction might be needed. For example, burying tubing may be the most economical method of maintaining thermal control, although framing above the ground should be considered if it offers a substantial cost saving, despite the fact that the daily and seasonal temperature variations on thermally unshielded tubes are large, and one runs the risk of more buckling, and especially time dependent outgassing of the tubes. A virtue of framing is accessibility to the tubes.

The experience at the VLA has bearing on alignment and stability of alignment. The spinal column of the VLA is a 6 cm cylindrical pressurized waveguide operated at carrier frequencies ranging from 20 to 50 GHz. The waveguide, oversize to reduce transmission loss, has an internal structure of wires to suppress waveguide modes other than those desired. The guide, enclosed in a mild steel tube, is buried at an average depth of 1.5 meters.

along the three 20 km legs of the VLA. The waveguide is used both to transmit information from any of the antennas to a central location, as well as to send timing information to the antennas to synchronize the local oscillators. The entire system is therefore "surveying" continuously by this timing information to an accuracy of ½ cm over 20 km , with direct validation of the "survey" by observation of point sources.

The present experience at the VLA is that they measure phase shifts in the system with a daily period equivalent to 10 cm over 20 km, the major part of these being due to thermal fluctuations of the transmission lines and couplings that lie above the ground. The fluctuating phase shifts due to the buried waveguide alone are thought to be less than 4 cm. One of the interesting results is that no large secular changes have been detected, indicating little if any earth shear and settling. The construction of the waveguide lines cost $160,000 per mile, the bulk of the cost being in the waveguide itself.

The vacuum system associated with both the MIT (Bates) Linac and the Stanford linear accelerator (SLAC) are clearly prototypes of those needed for the gravity antenna, albeit that they may be too costly. The MIT Bates Linac maintains pressures less than 1 x 10^{-6} mm of mercury in a 700' long 8" diameter stainless steel tube. The system employs titanium evapor ion pumps which operate without maintenance (no cryogenics, in particular) for years, providing there is no large gas load on the system. In order to bring the ion pumps into their operating region, prepumping of the system to 10^{-3} mm by other means is required. The SLAC installation, though different in scale and required.

The SLAC installation uses 4" diameter OFHC copper tubing in a central high vacuum chamber maintained by ion pumps. The copper tube, which serves as the waveguide and beam tube, is surrounded by a second chamber with higher pressure. SLAC is 2 miles long; nevertheless, it is regularly aligned to 1 mil in 2 miles, an angle of 1/1000 of a second of arc.

Stainless steel tubing and ion pumping have become the standard methods of obtaining high vacuum in gas stationary systems. Stainless steel tubing has many advantages -- its resistance to corrosion, relative ease and reliability of inert gas welding, and good outgassing properties -- but it is expensive. It is incumbent on a study of a large antenna to investigate the problems associated with using less expensive tubing -- aluminum tubing of all types, drawn, extruded, porthold died, and also standard schedule steel tubing, especially as regards its vacuum properties, which are bound to be worse than stainless steel, but which could be compensated for by an increased pumping speed of the vacuum system.

Both A.D. Little and Stone & Webster are interested in working on parts of these construction strategy problems.

Data Handling and Analysis - Experience in planning NASA space missions (RW) and carrying out high energy physics experiments (PL) has taught that considerable installation and recurrent costs are involved with data analysis and handling in a large project. Clearly, these costs should be included in a study of the style proposed. It is also important to begin evolving the data analysis and handling strategy in the early planning, as it can strongly influence the design of the experiment, especially in the configuration study.

In the gravity antenna project, there are three levels of data analysis and manipulation, broadly classified as control, regression, and signal analysis. The control function embraces processes as primitive as monitoring of antenna housekeeping information and putting it into a formated data stream for storage, to processes as subtle as computer (microprocessor) control of the interferometer alignment. The regression function relates to the correlation of the many parameters that are measured simultaneously in the antenna. Their analysis poses a significant computing effort. The output signal of an individual interferometer will contain noise of three sorts: that which is not correlated with any other measured variable, for example, thermal noise at the antenna endpoints; noise terms that are correlated with independently measured variables -- ground noise, laser intensity fluctuations, for example; and finally, noise terms that are correlated between separate interferometer outputs, such as the local gravity gradient noise, as well as the gravity radiation signal. Algorithms have to be invented to perform the regression function, which then produces a "cleaned" signal for the final signal analysis. Efficient digital techniques have to be developed for this last stage of the analysis, to establish criteria for pulse detection in the broadband outputs, as well as to search for periodicities.

Up to now, we have neglected this aspect of the experiment, even in our development of the prototype antenna. We hope to redress this, as discussed under the heading Computer. Furthermore, the project has the good fortune of having attracted Professor E. Wright of the MIT Physics Department, who is both interested in the astrophysics that could ultimately be uncovered by gravitational astronomy, but more to the immmediate point, is proficient in data analysis and the application of digital techniques to experiments. He has expressed interest in the data analysis part of the study.

RESEARCH PLAN AND BUDGET NARRATIVE

We are proposing an ambitious research program but one we believe to be necessary if the search for gravitational radiation from astrophysical sources is to come to fruition. We are committed to finishing the development of the prototype antenna, as there is much to learn from it, but it is now also time to see where we are headed. Out intuition is that it is possible to construct an antenna which will yield astrophysically interesting information. The increased optimism for the success and scientific value of a large gravitational wave antenna, as well as its possible applications to other scientific disciplines, has drawn new people into the project at MIT.

Approximately 2/3 of the proposed first year budget (and effort) is involved with: completing the prototype antenna, measuring its noise performance, the development of an active isolation system, and side experiments on the optics. This effort involves Weiss, Linsay, Shoemaker, Benford, an electronics technician, and two graduate students -- one student on the prototype antenna project, another on the development of isolation stages. This effort also includes all the equipment and materials and services budget.

The study of a large antenna system uses the remaining 1/3 of the first year budget. A possible plan for the study is schematized on the accompanying figure (p. 25a). In the first year the bulk of the effort, leading to the first conceptual design of a large antenna, will be carried out at MIT. Linsay will spend 1/2 time organizing and administering the study. To help in the study, we intend to fill a post-doctoral position with a physicist interested in the large antenna system. (Several qualified candidates have expressed a desire to work on this project.) Although the MIT group will work in concert, we will divide initial responsibilities in the following way. The post-doctoral scientist and Weiss will work on the optimal antenna configuration and the suppression of gravity gradient and seismic noise. Linsay and Wright will work on experiment design and the data analysis strategy. Ezekiel will study the optical design.

We will need help in the engineering, construction and cost aspects of the study in all of the three years. It is not realistic to look for this in the academic engineering departments of MIT as the engineering faculty carry out research of their own interest which does not necessarily intersect with our needs. Therefore we are going to outside commercial engineering firms to buy this help. We have chosen to consult with the engineering and consulting firm of Arthur D. Little Corporation, Cambridge, Mass and the engineering firm of Stone and Webster, Boston, Mass. Letters of intent from both of these companies as well as resumes of the staff they intend to make available to the study are attached at the end of this proposal.

Arthur D. Little has considerable engineering experience in optical, vacuum and thermal design. RW has had good experience with this company in thermal design studies of the COBE satellite project.

Stone and Webster is an engineering company primarily involved with large scale construction in the power industry; fossil as well as nuclear fuelled installations. Stone and Webster has close associations with MIT and views the gravity antenna project as means of maintaining these connections as well as enhancing corporate prestige. The antenna study, indeed even the construction of a large antenna were it to come about, would be of little financial consequence to this company. Stone and Webster would be involved in making trade off and parametric optimization studies of the conceptual design evolved by MIT and Arthur D. Little. They would also make the cost estimate of the final iteration of the conceptual design. Stone and Webster and MIT would produce the study report.

During the first year the focus of the study, is at MIT, nevertheless we would like to have use of the resources of both of these companies in a truly consulting mode, even though they will not have been assigned specific tasks. Furthermore, it is wise to get their advice as the initial conceptual design becomes formulated.

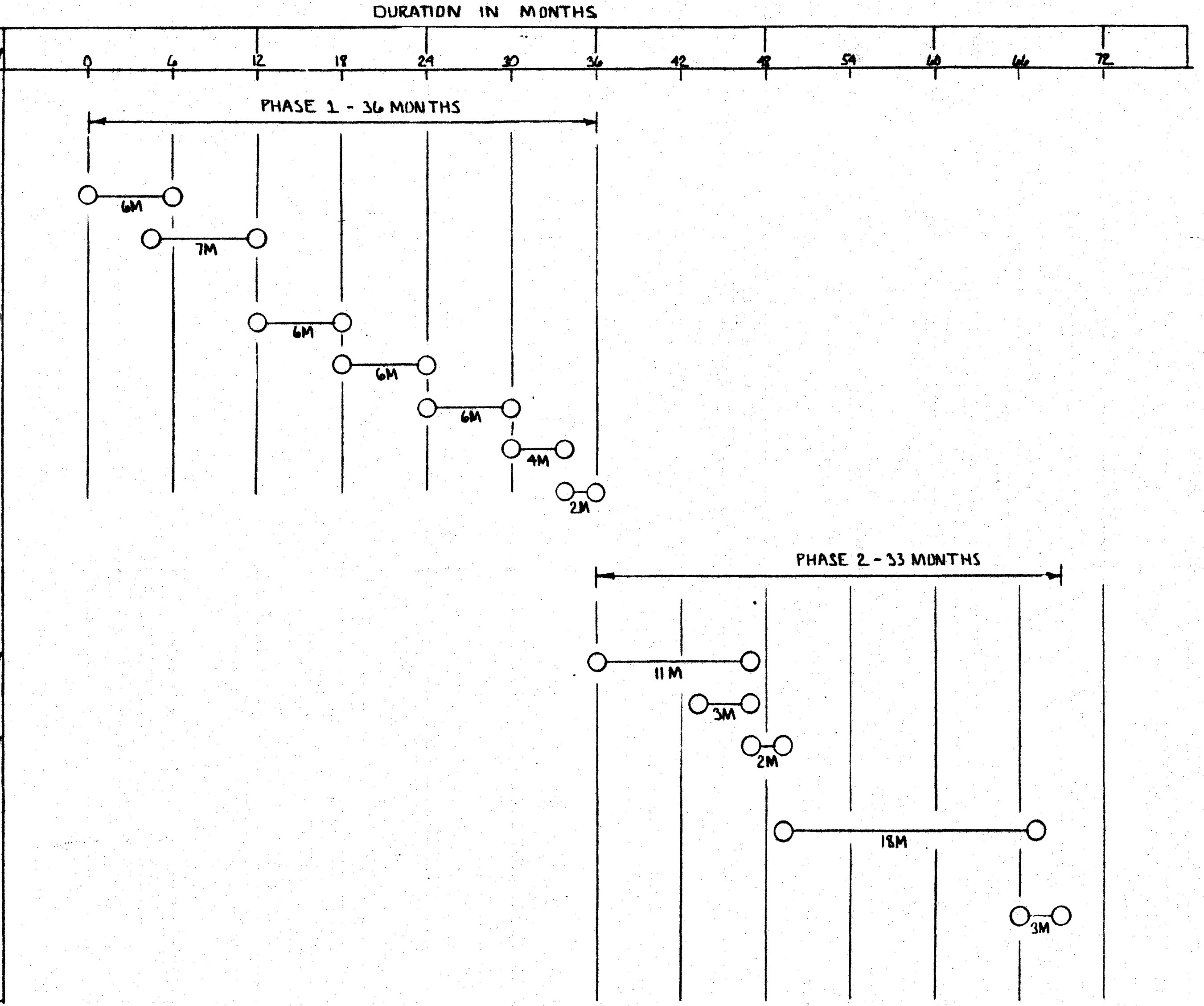
In the second year of the proposal, the emphasis and the larger fraction of the budget shift toward the study. The laboratory effort will become involved with specific engineering experiments suggested by the optical and mechanical design of the first phase of the study of the large antenna. We intend in this year to enhance our computing capability to develop modelling and data analysis algorithms for a large antenna (see section on computers).

In the second year of the study Arthur D. Little will be given specific tasks to analyze the optical,mechanical,and vacuum design while all three groups, Stone and Webster, Arthur D. Little, and MIT will carry out trade off and parametric optimization studies together.

In the third year of the proposal we anticipate that the laboratory work started in the second year will continue. We would like to augment it by studies of the noise properties of high power lasers. During this year the final iteration of the conceptual design of the large antenna and its cost estimate will be made.

The study results will be public information; however, they are most likely not publishable in the standard journals. The study could be an incidental publication of the MIT Press, or an NSF disseminated document. We hope the study will be the basis for the formation of an NSF sponsored Science Steering Group for Gravitational Astronomy, composed of all interested parties, as, if such a large project becomes a reality, it will require the support and wisdom of the entire community.

TASK	DESCRIPTION	RESPONSIBILITY
PHASE 1		
TASK 1	REQUIREMENTS DEFINITION	MIT
1A	DESIGN REQ'MNTS	MIT
1B	OPERATIONAL REQ'MNTS	MIT
TASK 2	CONCEPTUAL DESIGN	
2A	TRADE-OFF STUDIES	MIT/ADL/S&W
2B	PARAMETRIC OPTIMIZATION STUDIES	MIT/ADL/S&W
2C	CONCEPTUAL DESIGN DRAWINGS	S&W
2D	CONCEPTUAL ESTIMATE	S&W
TASK 3	PHASE 1 STUDY REPORT	MIT/S&W
PHASE 2		
TASK 4	FINAL DESIGN	
4A	DETAIL DESIGN	MIT/ADL/S&W
4B	DETAIL DESIGN ESTIMATE	S&W
4C	DETAIL DESIGN REPORT	MIT/ADL/S&W
TASK 5	CONSTRUCTION	S&W
TASK 6	START UP & TESTING	MIT/S&W



LEGEND:
MIT - MASS. INSTITUTE OF TECH.
ADL - ARTHUR D. LITTLE
S&W - STONE & WEBSTER

4	3	2	1	ISSUE
				PREP
				REVIEW
				APP
			3-26-81	DATE

GRAVITY WAVE ANTENNA
MILESTONE SCHEDULE

STONE & WEBSTER ENGINEERING CORPORATION

W.O. NO. 528.382.1

COMPUTER

At present our laboratory owns a PDP-11/20 computer bought in 1972. This computer has served in performing data analysis, on line experiment control and the small scale calculations involved in experiment design and modelling. The computer, now outdated, has become troublesome and is no longer serviced by the manufacturer so that we spend an increasing amount of our own time in repairing it. More important, the computer is inadequate to handle the data rate of the prototype antenna as well as the design modelling and development of data analysis algorithms we anticipate in planning the large antenna. It is clear to us that we have to upgrade our computer capability in the very near future.

The problem posed by the rapid development of computer hardware is how best to anticipate obsolescence? An approach which seems to be sensible is to rely on several small computers such as an LSI-11 to service and control sub systems as well as to format and prepare data for a central control computer. The control computer, having sufficient storage and speed, is then used in total experiment control and to perform the final data manipulations such as regression, correlation and spectral analysis. A strategy like this will certianly be needed in a large antenna system.

We would like to purchase an LSI-11 this year to gain experience with it as a sub system control computer on the prototype antenna. In the following year we intend to buy a larger computer, a VAX-11/750, which will be jointly funded by NASA for use on the COBE (Cosmic Background Explorer) Project and this NSF Proposal. We believe that a VAX-11/750 would be a better choice of computer for large processor than a PDP-11/60, despite its extra cost of roughly $30,000. The principle reason is that the VAX series will probably replace the large PDP-11 computers over the next ten years. In addition, the 750 is two to three times faster in execution than an 11/60, and is capable of expanding memory to two million bytes of core, ten times what is available on an 11/60.

PROGRESS DURING 1980

During the past year we have concentrated on finishing the construction of the interferometer. The two main tasks, now nearly complete, have been modification of the vacuum system and low noise damping of the free masses.

In order to permit changes in the alignment of the interferometer while it is under vacuum, we have added an XYZΘ manipulator to the pendulum support of each mass. Each manipulator is made up of three orthogonally mounted micrometer driven translation stages and a screw controlled rotation stage. A pair of vacuum bellows provide the coupling from each XYZΘ stage to the pendulum support in vacuum. Additional changes to the vacuum system were also made in order to simplify the electrical connections and the final assembly of the apparatus. These components are all complete and the vacuum system is now being leak tested and reassembled.

The main effort of the past year has been to build an electronic servo-system to provide low noise damping of the free masses. Without this feedback system to damp the motion induced by the ground noise, the mirror motion would be so large that it would be impossible to hold the interferometer locked on a single interference fringe. A block diagram of the servo loop is shown in Fig. 3. Seismic noise enters the system through the pendulum point of support. The motion is sensed by a capacitive bridge, which generates a signal that is fed back to the free mass through a damping capacitor. The low pass filter generates the correct transfer function to critically damp the motion of the mass. The overall effect of the servo loop is to electronically lock the mass to the table at low frequencies while allowing the mass to be free at high frequencies.

A block diagram of the bridge circuit and low pass filter is shown in Fig. 4. The bridge was designed to operate at RF because of the availability of very quiet electronics at these frequencies. The bridge amplifiers have an equivalent input noise at the bridge of 1.5nV/Hz. The circuits are assembled on printed circuit boards like that shown in Fig. 5. The sensing and damping capacitors (Fig. 6) are made of copper evaporated onto glass plates. Two sets of capacitors are mounted on each plate, in order to damp rotation about one axis, as well as damping the corresponding translational motion. If needed, we will be able to damp all six degrees of freedom of each mass.

The calculated spectral noise density of a mass (Fig. 7) indicates that we will be able to achieve the laser shot noise limit at frequencies above roughly 600 Hz. This limit is due to the electronic noise in the amplifiers driving the masses. The ultimate performance of the system is determined by the local seismic noise, which in the present set-up would not allow us to reach the shot noise limit below 300 Hz. The inertial response of a mass ($X_m(t)$, Fig. 8) to an impulsive force is heavily damped and is essentially gone after two seconds. The output of the bridge ($V_o(t)$, Fig. 8), which is approximately proportional to the acceleration of the mass, also decays with the same time constants. The time constants in the feedback loop were chosen to minimize the rms inertial motion of the mass rather than to achieve the fastest damping.

A third effort we have carried out this year has been to build an amplitude stabilizer for the laser light. The current scheme is a simple dc feedback loop, using a Pockels cell to modulate the beam (Fig. 9). If better performance is needed, we will build an RF loop, using the low noise circuits we have developed for the damping servo system.

A fourth effort during the past year has been the development of active seismic isolation systems. This is described in Appendix I.

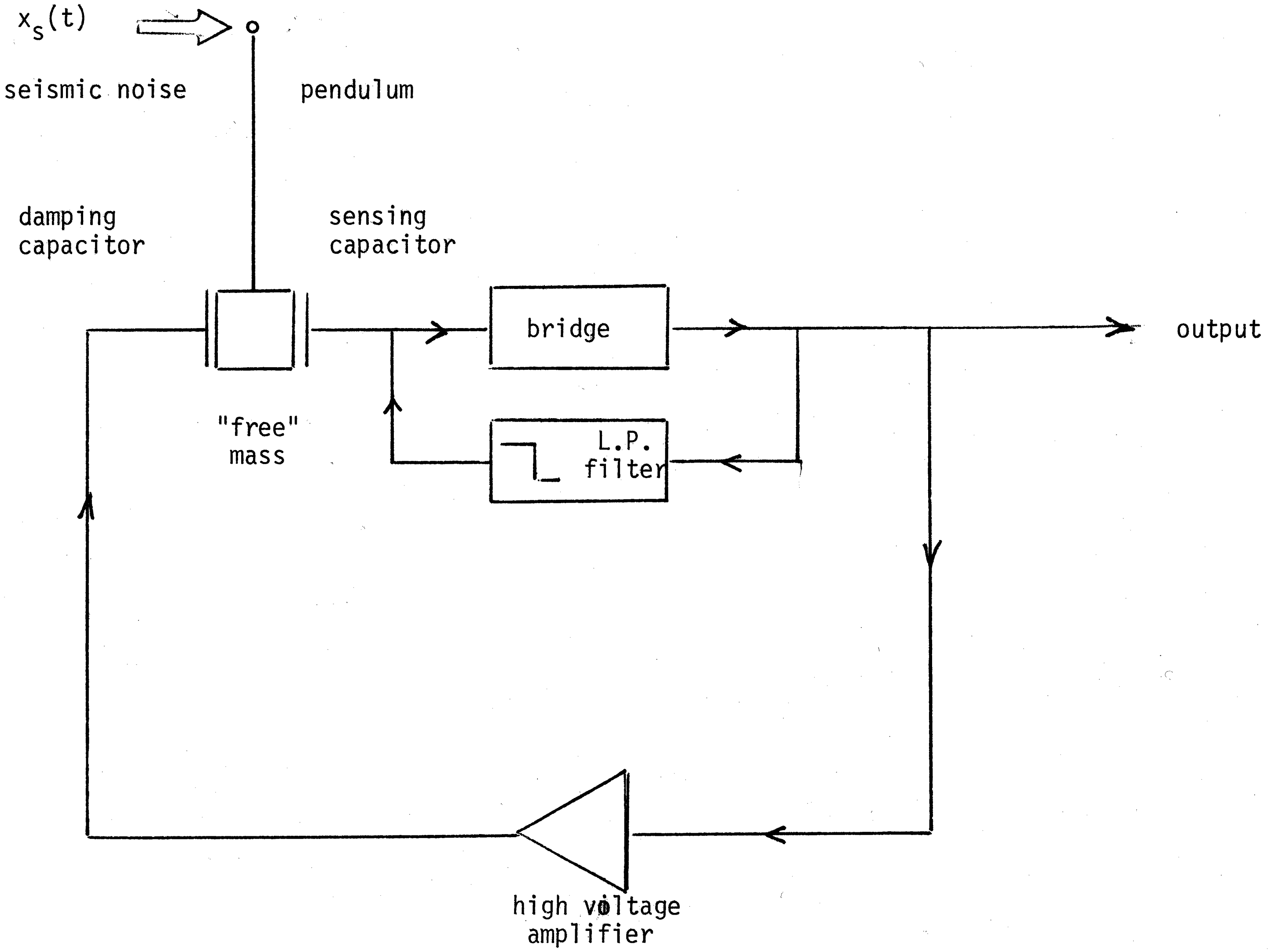

$x_s(t)$
seismic noise
pendulum
damping capacitor
sensing capacitor
bridge
output
"free" mass
L.P. filter
high voltage amplifier

FIG. 3

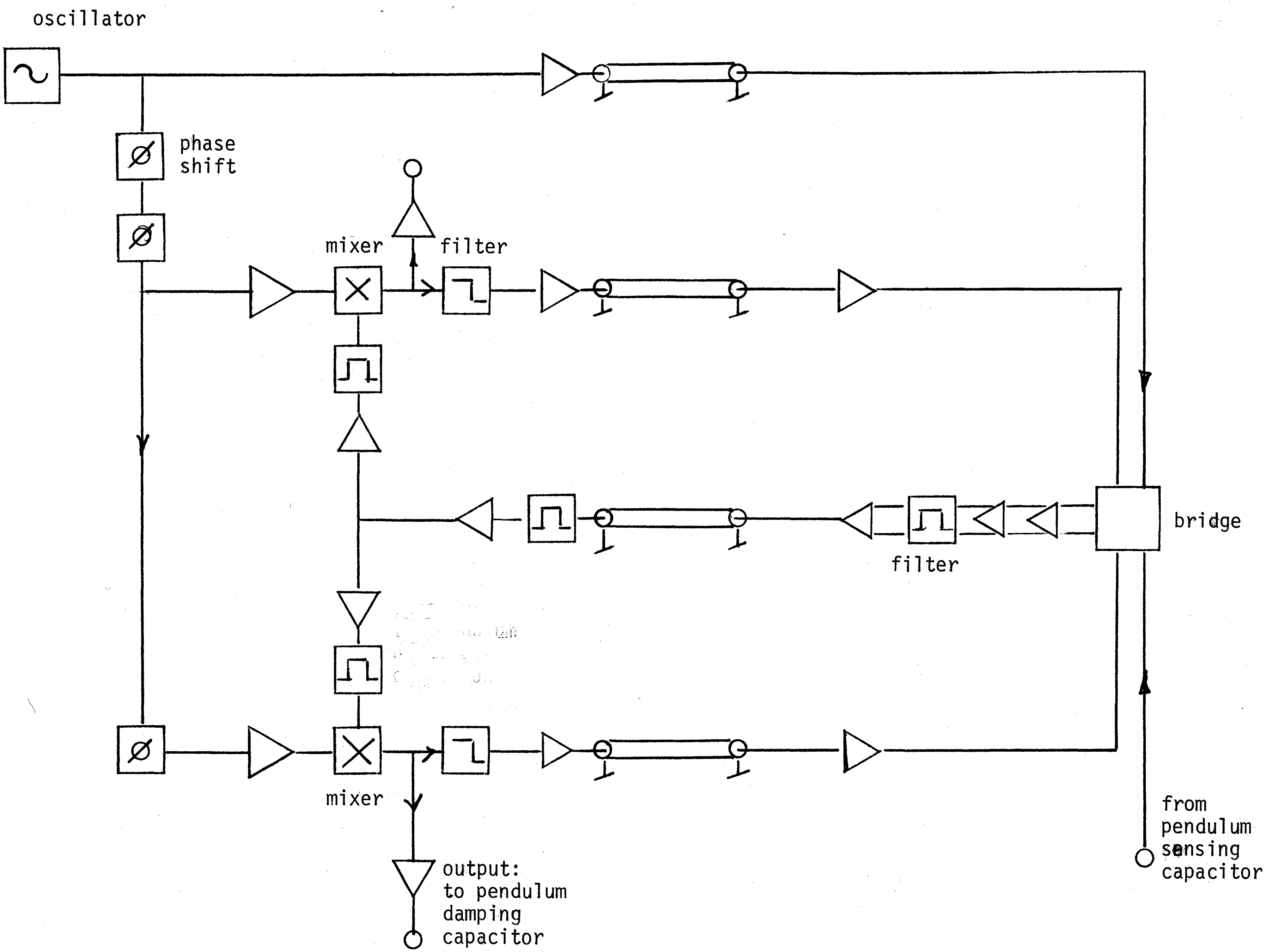

oscillator
phase
shift
mixer
filter
bridge
filter
mixer
output:
to pendulum
damping
capacitor
from
pendulum
sensing
capacitor

FIG. 4

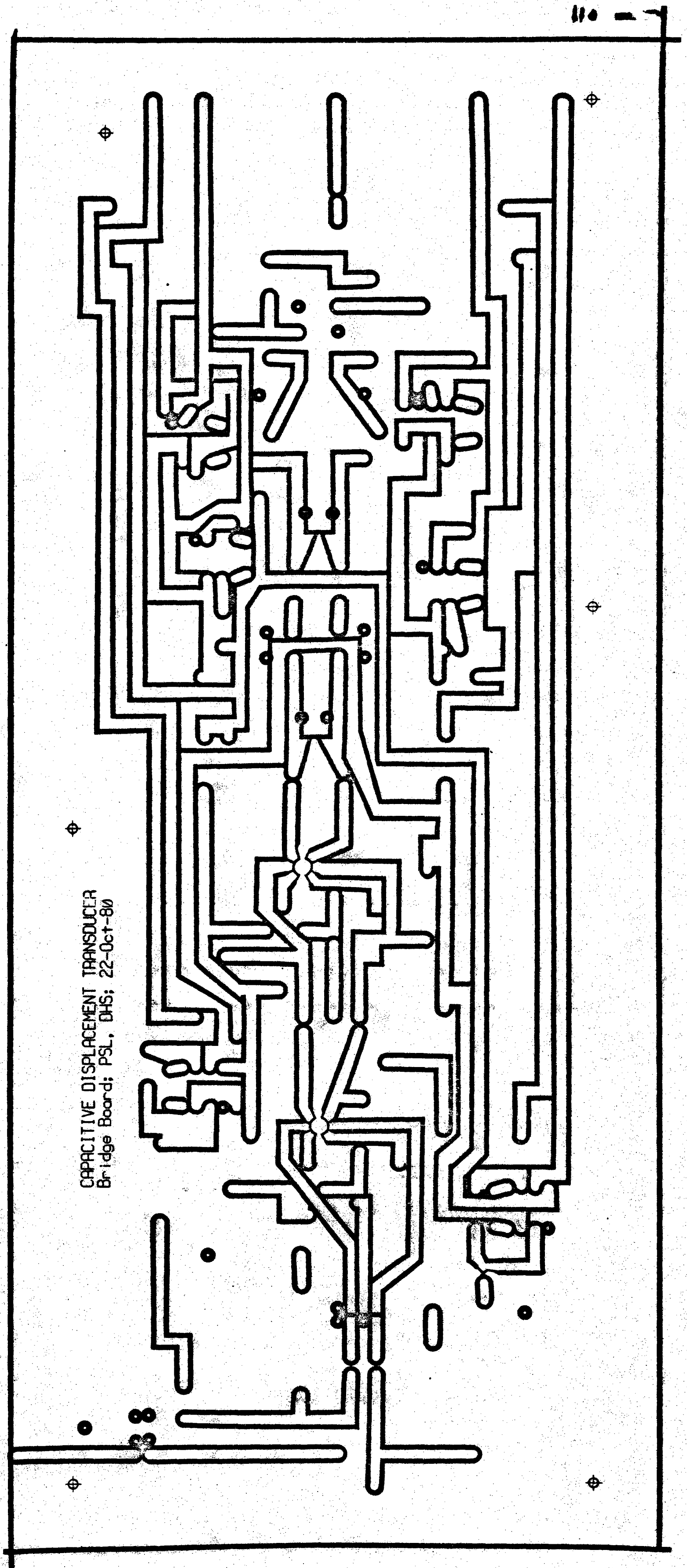

110
CAPACITIVE DISPLACEMENT TRANSDUCER
Bridge Board; PSL, DHS; 22-Oct-80

FIG. 5

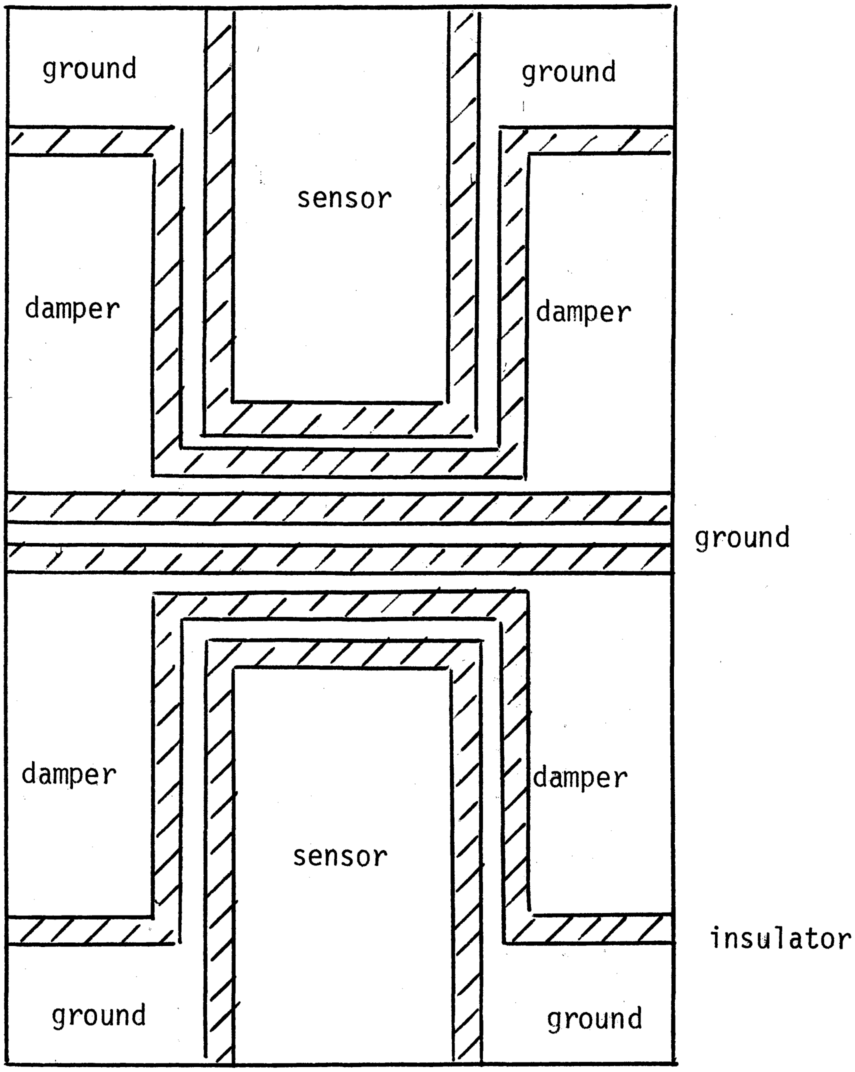

ground
ground
sensor
damper
damper
ground
damper
damper
sensor
insulator
ground
ground

FIG. 6

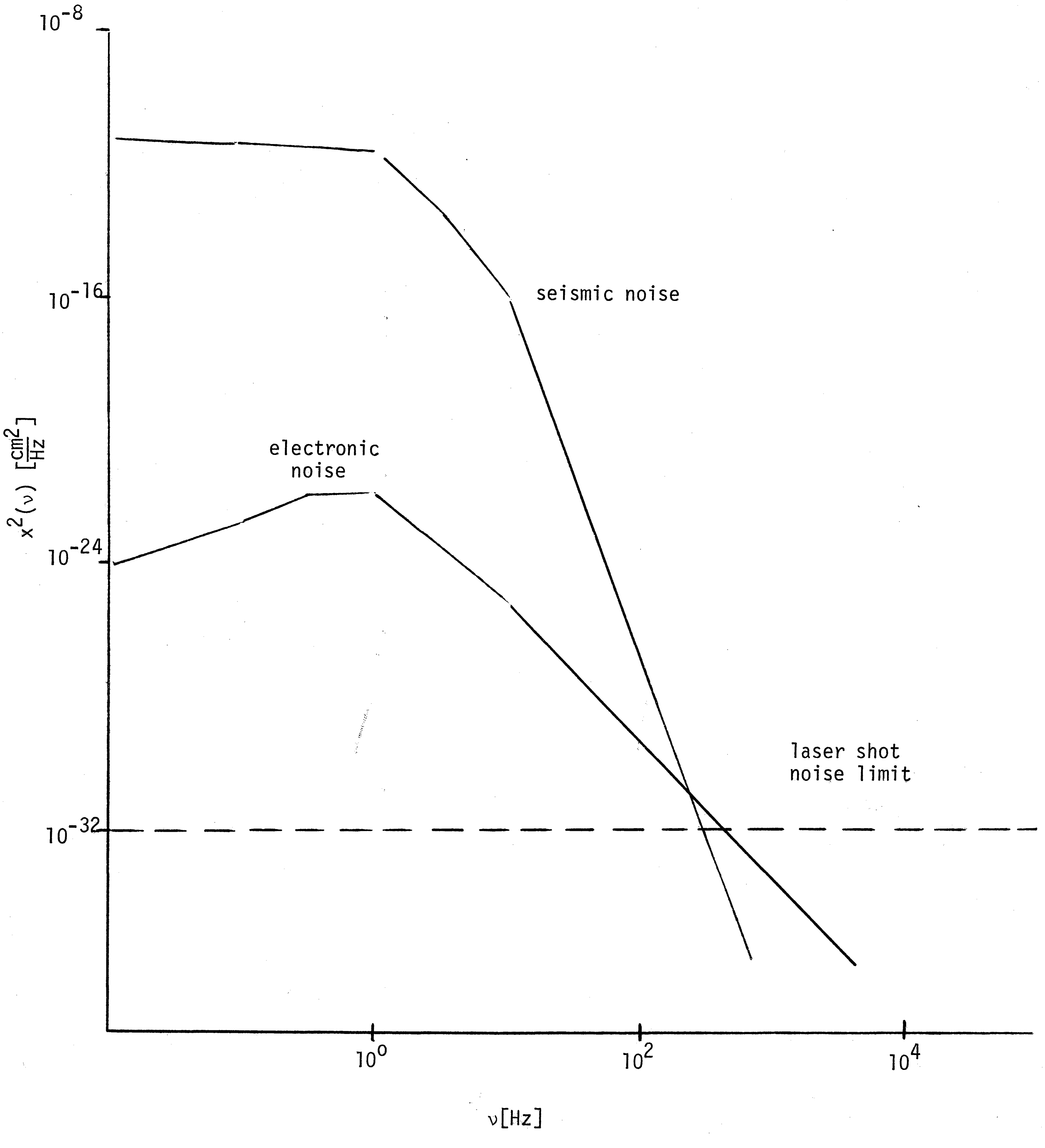

10^{-8}
10^{-16}
10^{-24}
10^{-32}
$x^2(\nu)\ [\frac{cm^2}{Hz}]$
seismic noise
electronic noise
laser shot noise limit
10^0
10^2
10^4
ν[Hz]

FIG. 7

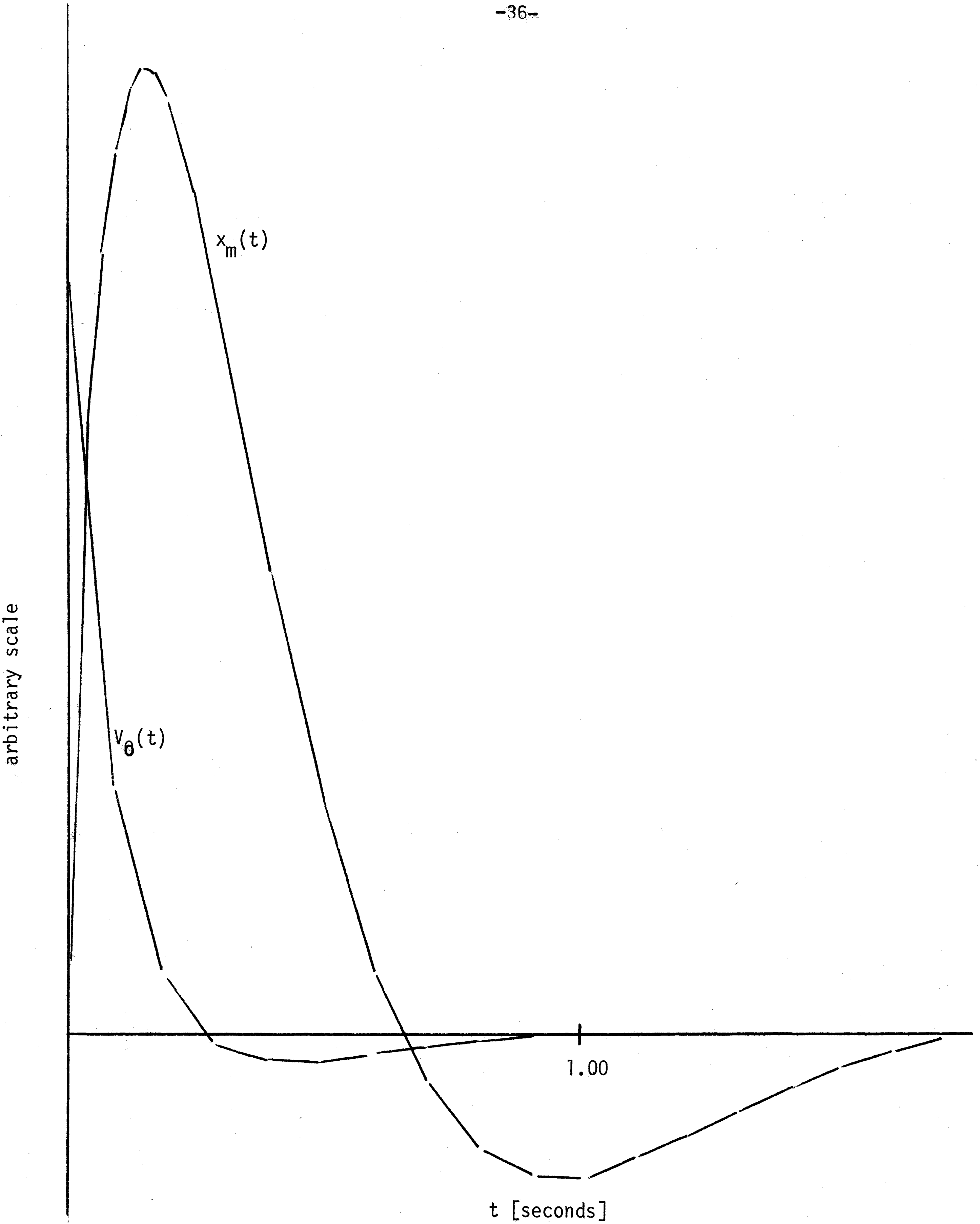


FIG. 8

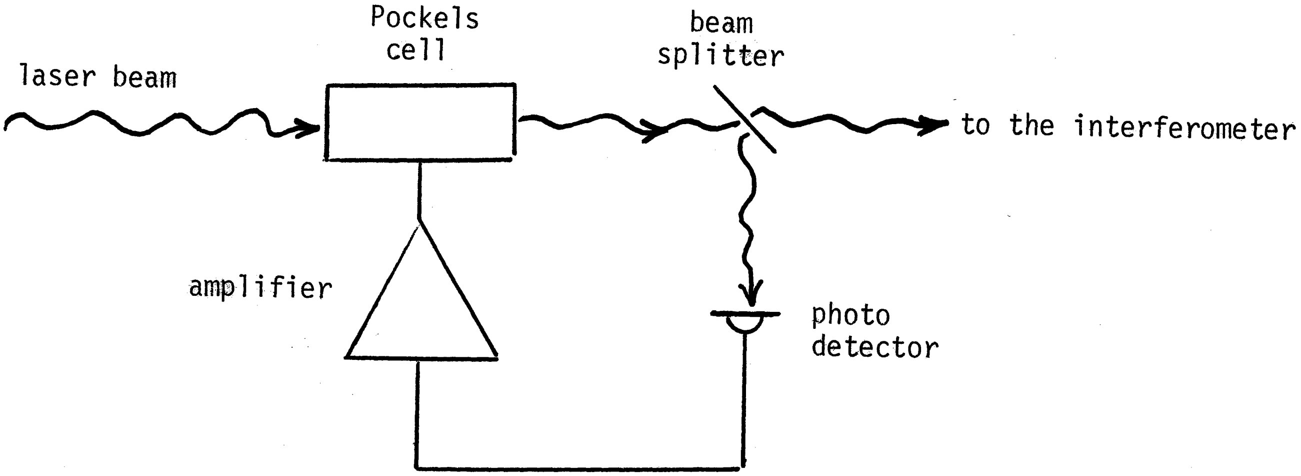

Pockels
cell
laser beam
beam
splitter
to the interferometer
amplifier
photo
detector

FIG. 9

APPENDIX I - ACTIVE SEISMIC ISOLATION

An ideally seismically isolated body is unaccelerated relative to inertial space - the reference frame determined by distant matter. Such a body experiences no net forces and, if furthermore it is an extended body, no torques about its center of mass - in other words it is a truly free mass. Terrestrially, it is necessary to support masses against earth gravity but this is no impediment to approximating a free mass as the support forces can be arranged to have an arbitrarily small gradient. It is, however, an enormous nuisance to work with free masses as anyone who has experimented with an almost astatic system knows (try it - an inverted pendulum supported by a cantilever spring is a good beginning). There is no stability.

The strategy we have adopted for seismic isolation is to shape the seismic transmission, by active means, to render the isolated mass effectively free in the frequency band of interest for gravitational wave detection. For broad band electromagnetically coupled antennas this is a more difficult enterprise than for single frequency acoustic antennas especially at low frequencies, f< 20HZ, where the promise for electromagnatically coupled antennas most probably lies. At still lower frequencies the limit due to local gravity gradient noise intrudes.

The time honored method of providing seismic isolation is to suspend with spring (electric, magnetic, mechanical, fluid) and a damper. For simplicity, let us consider only a one dimensional system (in the real world the other dimensions are extremely important, in fact are a source of a major problem through oscillator mode cross coupling) Refer to Figure 1; the ground motion relative to inertial space is $x_e(\omega)$ while the suspended mass motion driven through the spring and damper is $x_p(\omega)$. The magnitude of the suspended mass motion is

$$|x_p(\omega)| = \frac{|T_e(\omega)|}{|T_p(\omega)|}\,|x_e(\omega)| = \left|\frac{\omega_o^2 + \left(\frac{\omega\omega_o}{Q}\right)^2}{(\omega_o^2 - \omega^2) + \left(\frac{\omega\omega_o}{Q}\right)^2}\right|^{1/2} |x_e(\omega)|$$

the terms, which at this juncture appear like a cumborsome notation, are the following:

$$T_p(\omega) = K_p - m\omega^2 + j\frac{\omega\omega_o m}{Q}$$

is the transfer function relating suspended mass motion to applied force.

$$T_e(\omega) = K_p + j\frac{\omega\omega_o m}{Q}$$

is the transfer function that relates ground motion to force. Q, K, ω_o, and m have the usual meaning; quality factor , spring constant, driven resonance frequency, and mass. The seismic transmission is defined by the ratio

$$\frac{|x_p(\omega)|}{|x_e(\omega)|} = \begin{array}{ll} 1 \ ; & \omega/\omega_0 << 1 \\ Q \ ; & \omega = \omega_0 \\ (\frac{\omega_0}{\omega})^2 \ ; & \frac{\omega}{\omega_0} >> 1 \end{array}$$

There is no isolation at frequencies below the resonance; the resonance is the price paid for isolation at higher frequencies which varies only as fast as the inverse square of the frequency. Commercial vibration isolation systems are based on the above principle - Bendix, Barry Controls.....with lowest resonant frequency in the region of several Hertz, and critically damped - $Q \sim 1/2$ - to supress the resonance. The isolation varies more nearly as $1/\omega$ in this situation. These systems work moderately well, as any passenger of a car knows first hand, but are inadequate to isolate the ground noise at the levels required for gravitational wave research; especially at low frequencies where the ground noise amplitude excitation spectrum varies $\sim 1/f^4$. The naive directions in which to go are 1) reduce the resonant frequencies - and/or 2) compound isolation systems. Both of these are troublesome: reducing the resonant frequencies enough would lead to astatic and, therefore virtually unstable systems, while compounding isolation stages - clearly a part of any viable isolation scheme - has to be carried out judiciously otherwise the multiple coupled oscillators become unmanageable. In this as all other mechanical design the axiom for success is "free one mode at a time making all efforts to keep the resonant frequencies in the remaining modes as high as possible."

One solution we have mocked up in the laboratory in one dimension only, but with a plan to extending it to all three degrees of translation and rotation, is to use an accelerometer or seismometer mounted on the body to be isolated as a reference element in a null servo system. A controller, mounted on the ground exerts forces on the body to be isolated so as to drive the reference element to a null output. This implies that the body though still quite firmly attached to the ground is nevertheless vibration free relative to inertial space in a frequency band determined by the servo system filters. The resonance within the reference element as well as those of the isolated object (a platform) are damped electronically. The mechanical Q can be high so that the equivalent noise temperature of the reference is a few degrees Kelvin with moderate care in amplifier and transducer design. In a properly designed system of this sort the residual noise motion of the isolated object is limited by the Nyquist noise forces in the reference element, the displacement detector amplifier input noise and, to a lesser extent in a practical system, by the backreaction of the amplifier noise through the displacement transducer on the reference. The noise analysis is quite similar to the process of optimizing the signal to noise in acoustic gravitational antenna.

Ultimately such a system could be applied directly to the antenna masses or in a compound arrangement to the platform from which the antenna masses are themselves suspended.

The idea is quite old - in my life it stems from conversation with Bob Dicke in the early 1960's when he and I attempted an actively isolated system of this type but in which we tried to isolate all degrees of freedom on a single platform simultaneously. In short, the device did not work as not enough thought was put into the suppression of cross coupling of the multiple modes of this single system. Our present plan is to follow the axiom stated above.

The analysis of such a system in one dimension follows. The inertial reference (seismic) element mounted on the platform is itself used in a null servo configuration. Refer to figure 2. m_s is the seismic mass coupled to the platform through spring K_s and damper α_s. The displacement detector is a differential capacitor system with the outer plates tied to the platform. $T_1(\omega)$ is the voltage to voltage transfer function of the phase sensitive demodulator and amplifier while $T_2(\omega)$ includes the servo filters and the conversion of output voltage to applied force F_c. F_c in the present system is provided by a loudspeaker movement linear motor. The noise in the system is characterized by current and voltage noise sources at the amplifier input as well as by the thermal Nyquist force, F_{th}, acting on the seismic reference mass directly. The equation of motion of the seismic mass is:

$$T_s(\omega)\ x_s(\omega) = F_{th}(\omega) + F_{Br}(\omega) + T_{sp}(\omega)\ x_p(\omega) + F_c(\omega)$$

where

$$T_s(\omega) = -m_s\omega^2 + K_s + \frac{j\omega\omega_{os}m_s}{Q_s} \qquad \alpha_s = \frac{\omega_{os}\ m_s}{Q_s}$$

$$T_{sp}(\omega) = K_s + j\omega\omega_{os}m_s$$

The output voltage is

$$V_{out}(\omega) = T_1(\omega)\ [(X_s(\omega) - X_p(\omega))\ \frac{Vo}{d} + e_n^x(\omega)\ ]$$

where $e_n^x(\omega) = (e_n^2(\omega) + i_n(\omega)Z^2)^{1/2}$

Z is the source impedence of the capactive transducer, it is equal to $1/j\ \omega c$ where omega is the capacitor bridge drive frequency. The control force is given by

$$F_c(\omega) = T_2(\omega)\ V_{out}(\omega)$$

The two direct noise forces are the Nyquist force spectral density

$$F^2{}_{th}(\omega) = \frac{4KTm_s\omega_{os}}{Q_s}$$

and the amplifier-transducer back reaction force density

$$F^2_{BR}(\omega) = \left(\frac{1}{2\pi}\ \frac{A}{d^2}\ \alpha^2\ V_o\right)^2\ i^2_n(\omega)Z^2 \qquad \alpha = \frac{1}{300} \quad \text{cgs to MKS conversion}$$

A is the plate area.

Combining the equation, noting that the noise terms combine in squares, gives

$$V_{out}(\omega) = \frac{\frac{T(\omega)}{1}\ \frac{Vo}{d}\ \left[\left(F^2_{th}(\omega) + F^2_{BR}(\omega) + \left(T_s(\omega)\frac{d}{V_o}\right)^2\ e^2_n(\omega)\ \right)^{1/2} + m_s\omega^2 x_p(\omega)\ \right]}{\left(T_S\ (\omega) - T_1(\omega)\ T_2(\omega)\ \frac{Vo}{d}\right)}$$

It is interesting to note that if the amplifer noise sources are matched to the transducer impedence the optimum capacitor drive voltage, assuming that the thermal noise can be made negligible, is given by

$$V_{o_{optimum}} = \frac{2^{1/4}}{\alpha}\ \left(\frac{2\Pi|T_s(\omega)|d^3}{A}\right)^{1/2}$$

Next the equation of motion of the platform driven by the ground motion and the seismic-reference output are considered. Refer to figure 3. m_p is the platform mass coupled to the ground by spring K_p and damper α_p. The reference output signal is filtered by $T_3(\omega)$ and applied to controller F_c, again a linear motor (part of a computer disc drive - a glorified loudspeaker movement able to provide kilograms of force). A general noise force, F_n, on the platform is included in the analysis to accommodate acoustic and other disturbances not coupled from the ground. The equation of motion for this system is

$$T_p(\omega)X_p(\omega) \cong F_N(\omega) + F_C(\omega) + T_e(\omega)X_e(\omega)$$

The approximate equality is used to indicate that the direct force due to the reaction of the seismic reference on the platform have been neglected in this simple presentation. They complicate the analysis and are furthermore not important terms if the reference element is itself incorporated in a null servo system. The control force is

$$F_C(\omega) = T_3(\omega)\ V_{out}(\omega)$$

The closed feedback loop response of the platform determined by combining the above equations is given by

$$X_p(\omega) = \frac{T(\omega)\ \left[\left(F_{th}^2(\omega) + F_{BR}^2(\omega) + \left(T_S(\omega)\ \frac{d}{V_o}\right)^2 e_n^2(\omega) + \frac{F_n^2(\omega)}{T^2(\omega)}\ \right)\right]^{1/2} + T_e X_e(\omega)}{T_p(\omega)\ -\ T(\omega)m_s\omega^2}$$

where $T(\omega) = \dfrac{T_3(\omega)\ T_1(\omega)\ \frac{Vo}{d}}{T_s(\omega)\ - T_1(\omega)T_2(\omega)\frac{Vo}{d}}$ is the forward transfer function of the system.

In the limit of large forward gains,

$|T(\omega)\ m_s\omega^2| >> |T_p(\omega)|$, the motion of the platform is determined by the reference element intrinsic noise.

$$X_p(\omega) \longrightarrow \frac{[F_{th}^2(\omega) + F_{BR}^2(\omega) + (T_s(\omega)\ \frac{d}{Vo})^2\ e_n^2\ (\omega)]^{1/2}}{M_s\omega^2}$$

We have constructed and tested a demonstration of this type of isolation system. The system used a commercially available (Kinemetrics) feedback accelerometer as reference element. The limitation in the present system stems from this unmodified accelerometer due to its large amplifier noise and limited bandwidth. The results are sufficiently encouraging to pursue this concept: first, by modifying the accelerometer with our quiet and broadband RF displacement sensor electronics and secondly by extending the system to all three dimensions. The parameters of the demonstration system are

Reference element

$m_s = 3$ grams $\qquad f_{os} = 14\text{Hz} \qquad Q_{os} = 10$

$T_2(\omega) = 1.2 \times 10^3$ dynes/volt $\qquad$ flat to 50 Hz

$e_n(\omega) \sim 4 \times 10^{-8}\ \text{v/Hz}^{1/2}$, $\quad i_n(\omega) \sim 1 \times 10^{-13}\ \text{amp/Hz}^{1/2} \qquad Z_t \sim 1.5 \times 10^6\ \Omega$

Platform

$m_p = 9.5 \times 10^3$ grams $\qquad f_{op} = 3.081$ Hz $\qquad Q_{op} = 20$

$$T_3(\omega) = 3.6 \times 10^9\ (\text{dynes/volt})\ \frac{j\,\omega\,\tau_d}{(1 + j\omega\tau_d)\,(1 + j\omega\,\tau_{int})}$$

$\tau_d = 33$ sec, $\qquad \tau_{int} = 4.7$ sec

The performance of the system is shown in figure 4 which shows the platform acceleration spectrum as observed with both the servo on and off. The ground noise attenuation at low frequency is limited by the finite forward loop bandwidth determined by the commercial accelerometer electronics while at higher frequencies the spectra are dominated by amplifier current noise. The electronics can be improved by a factor of 10 before the thermal noise in this accelerometer becomes dominant.

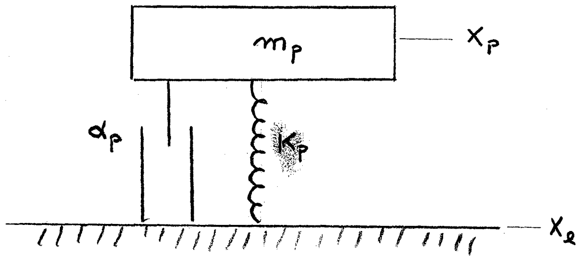


Fig.1 A simple isolation stage

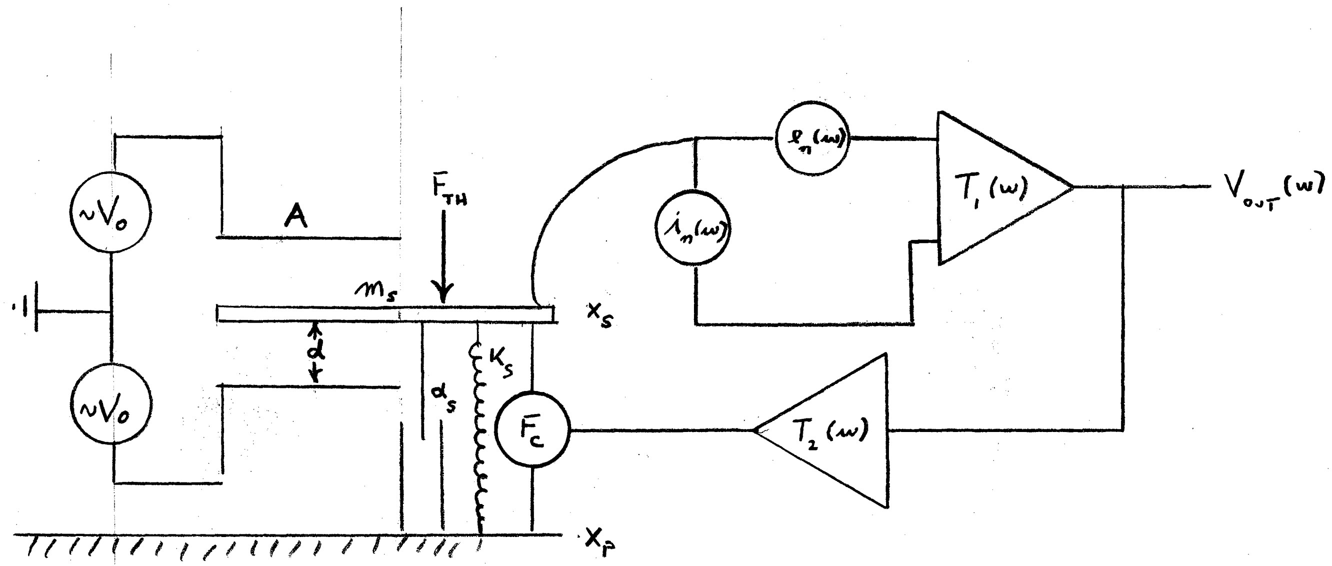


Fig.2 Inertial reference incorporated in a null servo loop

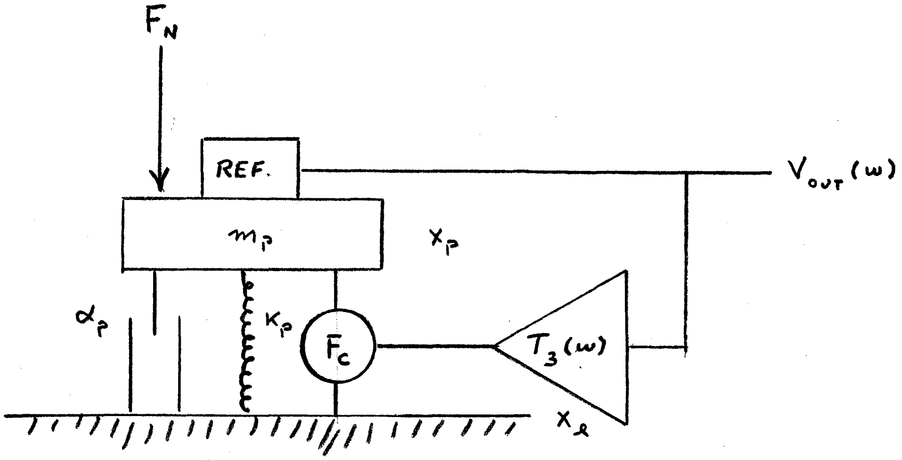


Fig.3 Active isolation stage incorporating reference in a null servo loop

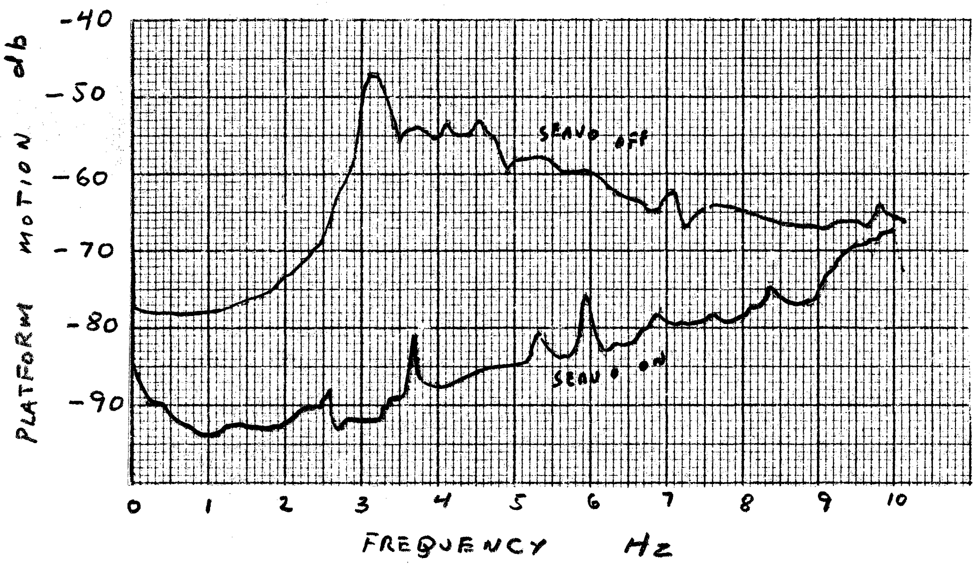


Fig.4 Sample acceleration spectra of the demonstration active isolation system. 0 db corresponds to 13.8 $\mathrm{cm/sec^2/Hz^{1/2}}$

APPENDIX II - DESCRIPTION OF THE PROTOTYPE ANTENNA (from 1978 Proposal)

A schematic drawing of the antenna now partially constructed at MIT is shown in Figure 1. Three masses are suspended on horizontal seismometer mounts in high vaccuum ($P < 10^{-7}$ torr). The three masses are the mirror mounts of an equal arm Michelson interferometer illuminated by a commercial 1-watt Argon ion laser. Each interferometer arm is a 1.3 meter long reentrant optical delay line comprised of dielectric coated spherical mirrors in a near confocal configuration. The laser beam is split by a 50-50 beam splitter and enters the delay lines through a hole in the spherical mirrors. The beam makes approximately 200 passes in each cavity before reemerging through the same hole by which it entered. The emerging beam passes through Pockel's cell phase shifters and is recombined by the beam splitter after which it is detected by a water cooled PIN Silicon photo diode.

The interferometer is held on a fixed point of a single fringe by a servo system using electro-optic (Pockel's cell) phase shifters as controllers and modulators. The servo error signal is derived by modulating the optical phase in oppositely polarized Pockel's cells in the two interferometer arms by $\pm\ \pi/4$ at a 3 MHz rate. The fringe phase modulation is synchronously demodulated yielding an error signal which is applied to the controllers to maintain the fringe modulation symmetry. This signal is proportional to the differential displacement of the antenna masses and is the antenna output. The error signal is applied to the Pockel's cell phase modulators to control small amplitude high frequency fringe excursions and after low pass filtering to electrostatic controllers that apply forces directly on the antenna masses to control large amplitude low frequency excitations. The antenna operated as a null servo system is insensitive

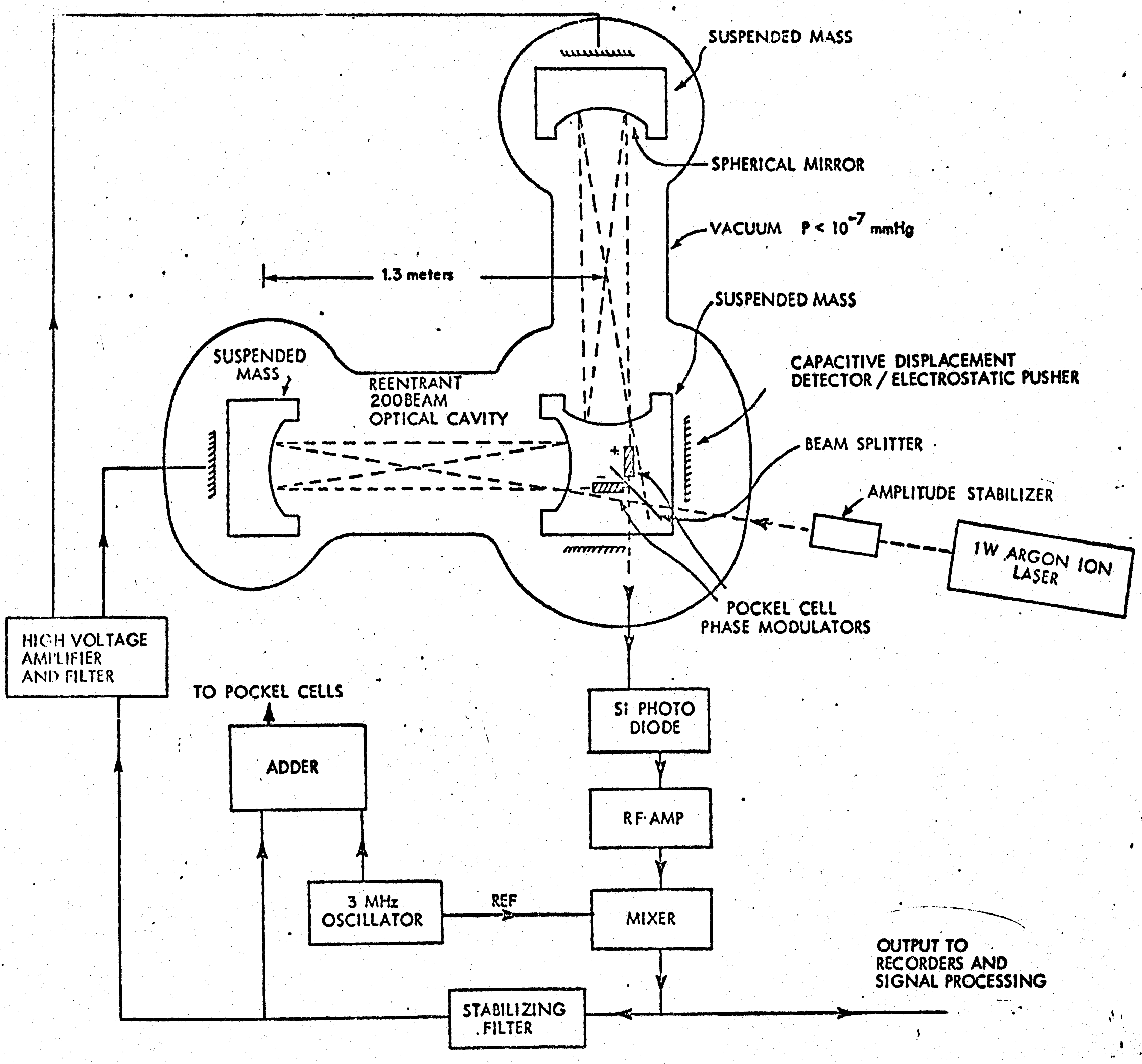


FIG. 1. Schematic drawing of the antenna being constructed at MIT.

to gain variations and has reduced sensitivity to laser amplitude noise at frequencies other than the modulation frequency. The open loop gain of the servo is, however, not sufficient to accommodate the full extent of the low frequency amplitude noise of the commercial argon laser. An external amplitude stabilizing servo system employing an electro-optic amplitude modulator is used between the laser and the interferometer to reduce the amplitude noise due to plasma oscillations and acoustic noise to acceptable limits.

The frequency stability of the laser is not critical provided that the difference in optical delay in the two interferometer arms is much less than the reciprocal of the oscillating laser line width.

The multipass delay lines that comprise the interferometer arms are useful components in an interferometric antenna as long as the Poisson amplitude noise dominates the antenna noise budget and the delay line storage times remain less than 1/2 the period of the gravitational wave. For fixed laser power, the multipass arms increase the fringe phase sensitivity of the interferometer by the number of passes per arm. The number of passes is limited by the reflectivity and optical quality of the mirror surfaces.

As long as the Poisson amplitude noise is dominant, the optical delay line is equivalent to increasing the length of the antenna; however, at those frequencies where noise sources, such as thermal and ground noise, that physically move the end mass dominate, the only way to increase the signal-to-noise ratio is to actually increase the antenna baseline.

Optical delay lines using spherical mirrors have been described by Herriott. D. K. Owens at MIT has studied and constructed delay lines using spherical mirrors. He has discovered several interesting and useful properties of these delay lines. The most encouraging one is that the delay lines are easy to align. If the reentrant condition is satisfied, namely that the input and output beams pass through the same hole, the delay line behaves as though the beam is reflected by the back of the front surface of the mirror which has the coupling hole in it. The position of the output beam is independent of the transverse position and angle of the far mirror as long as the beam pattern does not spill off of the mirrors. If the reentrant condition is satisfied, the time delay of the beam in the cavity is insensitive in first order to transverse motions and rotations of the far mirror.

The mirrors in the prototype antenna are 4 inches in diameter, have a radius of 1.3 meters,a reflectivity of 99.5% at 5145A and are good to 1/10 of a wavelength over their entire surface. The coupling hole has a diameter of 2.5 mm.

The design of the suspensions for the antenna masses has defied a simple, elegant and economical solution. The suspensions have to satisfy several conditions. First, they must have a high Q to reduce the coupling to thermal fluctuations. Second, they must provide isolation from ground and acoustic noise. What makes the problem difficult is the inevitable collection of normal modes of motion of a mechanical system which cross-couple and by parametric conversion transfer energy between each other. In other words, the isolation calculated for a long period suspension is never realized in practice because the suspension structure has its own resonances that couple into the principle mode of the suspension. This is a problem that has long been recognized in the design of seismometers and gravimeters. A rule of thumb to minimize this problem in suspensions is to keep them simple and to force the resonances of the structural members toward high frequencies.

STONE & WEBSTER ENGINEERING CORPORATION

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March 27, 1981

Professor Rainer Weiss/
Scientist Paul S. Linsay
Department of Physics, Room No. 20F-001
Massachusetts Institute of Technology
Cambridge, MA 02139

W.O. 528.382.1

Dear Sirs:

NATIONAL SCIENCE FOUNDATION
PROPOSAL FOR "INTERFEROMETRIC
BROAD BAND GRAVITATIONAL ANTENNA"

We appreciate the opportunity to have discussed with you, in greater detail than previously, the project requirements and possible project schedule to support your NSF proposal on gravitational wave detection and measurement. Based on these discussions we understand that the Conceptual Design (Phase 1) would consist of several Tasks and Sub-Tasks that would be scheduled over approximately a three-year period. Task 1, which would cover the design and operational requirements, would be undertaken almost entirely by MIT and cover a period of about a year. Our involvment would essentially commence on Task 2. This Task would undertake, as a sub-task, the important trade-off studies (cost vs technical feasibility and constructability) of the vacuum system, laser beam enclosure and other design considerations. Stone & Webster (S&W) would participate with MIT and Arthur D. Little (ADL) in accomplishing the trade studies. Other Task 2 Sub-Tasks would cover conceptual design sketches and site arrangement drawings and a conceptual design estimate all of which would be coordinated by S&W. The Phase I effort would be completed by accomplishing Task 3, the Phase I Conceptual Design Report, which would be undertaken by MIT with contributions as necessary by S&W and ADL.

We understand a Phase II effort would be contingent on the results of the Phase I effort and NSF funding. Phase II would involve detailed design, construction, start-up and testing. S&W would have major involvement in Phase II, which might cover a period of 2 1/2 to 4 years.

Stone & Webster agrees to support the Massachusetts Institute of Technology as a Sub-Contractor in Phases I and II. We propose to provide our services on a cost-reimbursable basis. Approved or provisional Government overhead rates will be used and our fee will be consistent with the type and value of services provided. Specifics of our scope-of-work, level of effort, expected cost, type of contract, and terms and conditions are to be negotiated.

We would expect to assign this work to our Advanced Technology Section where it would be handled by senior engineers or scientists experienced in a variety of similar projects and studies. Typical of the qualifications of staff we would assign are Dr. George East, Mr. Robert DeLuca and Mr. Robert Tschirch who would work under the direction of Mr. Donald Guild, Head of the Advanced Technology Section. Resumes of these individuals are attached for your information.

As you are aware, Stone & Webster and MIT have a long history that includes joint involvement in numerous projects. As a major international firm we are probably best known for the larger chemical, hydroelectric, fossil and nuclear power plants that we have successfully designed and constructed; we also have substantial experience in the design and construction of a variety of smaller projects that were very complex in the design and construction challenges that we successfully resolved. Attached is a general capabilities brochure that describes some of the conventional type of projects where we were involved as well as our most recent Annual Report. Also attached are copies of a work schedule that we prepared to reflect the schedule and involvement of our effort as you described it to us.

Should you have further questions, please contact Don Guild (617/973-2501), Paul Riegelhaupt (617/973-0954), or our Manager of Government Marketing, Robert Paine (617/973-0060).

Very truly yours,

J N White

J. N. White
Vice President

Encl. - Resumes (20 ea)
- Brochures (20 ea)
- Schedule (20 ea)

Arthur D. Little, Inc. ACORN PARK · CAMBRIDGE MA 02140 · (617) 864-5770 · TELEX 921436

16 March 1981

Dr. Rainer Weiss
20F 001
Massachusetts Institute of Technology
Cambridge, MA 02139

Dear Ray: 92912

This is to confirm our telephone conversation of today, and to transmit the attached Arthur D. Little, Inc., qualifications to support your study program on the prototype (full scale) gravitational antenna. The qualifications contain examples of relevant experience plus resumes of staff members who could participate in the study. The specific areas of our study, and the concentration in these areas would determine who would participate, and to what degree.

I believe we can make the best contribution to your study in two areas: Construction Strategy and Optics. In these areas, we would assist the MIT team in generating the conceptual design of the structural/vacuum system and the optical system. In the construction Strategy area, this would consist of performing technical and/or technical/cost tradeoffs in the areas of mechanical and thermal design, vibration isolation, material selection, and vacuum pumping system design. In the optics area our support could include an engineering design comparison of the optical interferometer approaches including laser source characteristics, point accuracy, beam diameters, sensing mechanisms, delay line configuration, and/or other optical problems which you feel need consideration in the engineering design portions of the study. Specific tasks, and their scope would be mutually agreed upon during the course of the study. We would also be willing to cooperate with any other subcontractors on your project whose areas of participation interfaced with our areas.

We look forward to the possibility of working with you on this project, and would be pleased to submit a proposal to you at an appropriate time. Please call me if you would like further information.

Very truly yours,

Warren

R. Warren Breckenridge

RWB:rsd
Encl. (2 sets)