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

Massachusetts Institute of Technology

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PRINCIPAL INVESTIGATOR(S)

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

TITLE OF PROJECT

"Interferometric Broad Band Gravitational Antenna"

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

We are continuing the development of a prototype laser interferometric gravitational antenna, and are studying the design, siting, and costs of a large antenna system (5 to 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 a research program with the aim of detecting gravitational radiation from astrophysical sources. The present guarded but optimistic guess for the sensitivity required of an antenna system to detect periodic, transient, and chaotic sources is a strain sensitivity of $10^{-23}/\mathrm{Hz}^{1/2}$ at 1 KHz rising to $10^{-21}/\mathrm{Hz}^{1/2}$ at 30 Hz. In principle, this can be achieved with a pair of long baseline interferometric antennas at sufficient separation.

The proposed program consists of several pieces: 1) The demonstration of displacement sensitivities at the level of 10^{-16} cm/$\mathrm{Hz}^{1/2}$ in a small prototype interferometric antenna. 2) A study of the design, siting, construction and costs of a pair of 5 to 10 Km gravitational antenna comprising the gravitational wave receiving system. 3) A set of technical questions derivative of the study that require experimental work. These include: design and testing of active ground noise isolation strategies, measurements of possible millisecond fluctuations in the outgasing of vacuum systems, the development of techniques for handling high optical power in light fibers and electro-optic modulators.

RESEARCH IN THE PAST YEAR

Prototype Antenna

The prototype 1.5 meter antenna is in the last stages of assembly and will hopefully be tested in its complete version in April or May of 1983. The assembly will constitute a substantial achievement. It signifies the completion of a great deal of technology, including 18 mass stabilizer servoes, a laser amplitude stabilization servo, laser phase modulation interrogation schemes, fiber optic couplers. The last year was spent primarily on completing the mass stabilization servo system, developing the fiber optic coupler and evolving a strategy for the alignment of the instrument.

Work is far along on a scheme to impress wide band phase noise on the laser light to reduce the noise from scattering in the prototype antenna. The concept has important applications to a large antenna as its success would reduce mirror size and vacuum system diameter. It is hope to have the phase noise modulator ready to use on the prototype late in the spring of 1983.

A small evacuated instrumented Michelson interferometer has been constructed for use as a phase and amplitude noise spectrum analyzer. It will find application in determining the properties of the phase noise modulation system, as well as in separating the laser related noise terms from the host of other noises that may occur in the prototype antenna.

Other Experimental Projects

The one dimensional active ground noise isolation system has been refined to the point where the stabilized platform motion is limited to the thermal noise of the seismic transducer in the 1 to 10 Hz band. The system approaches 60 db of ground noise isolation in this band.

A description of the system is to be published in RSI (Appendix III). Continuing work with ground noise isolation systems will be described under the section "work proposed for the coming year."

Large Baseline Antenna Study

During the past year we have evolved a conceptual design of a large antenna system with sufficient detail to allow a first cost estimate to be made. We have carried out this study with the engineering and consulting firms of Arthur D. Little of Cambridge, Massachusetts and Stone and Webster of Boston, Massachusetts. The design and costs of the vacuum system and some of the optical engineering questions were addressed by Arthur D. Little, while Stone and Webster made the estimate of the construction and installation costs.

A brief summary of the study findings are given here. In the study of the vacuum system, aluminum, stainless steel and cold-rolled steel vacuum pipe of diameter 12" to 36" were considered. Various pumping systems using ion pumps, diffusion pumps and cryo pumping were analyzed. The system chosen for further study uses 24" aluminum tubing pumped by ion pumps to maintain the vacuum. Costs were evolved for a complete system including roughing pump, valves and specialized welding and cleaning techniques that would be required in a remote site installation. The choice of 24" tubing was based on calculations of the diffraction properties of delay line optics using phase noise destruction of the laser temporal coherence.

A top down estimate for remote site construction was carried out by Stone and Webster on the assumptions: the site was benign, no large rocks, no extensive grading had to be carried out, the tubes would be placed on concrete pillars, alignment would be done by microwave thoedilite, and an enclosure surrounding the vacuum tubes would be used to temperature regulate to ±10°C. Estimates were made for the power and water requirements. MIT made estimates of the instrumentation costs and the end mass enclosure vacuum systems.

At present, the estimates for an antenna are:

	Fixed	$/Km
Installation and construction	3100K	1100 K/Km
Vacuum system	120K	356 K/Km
Instrumentation	5300 K	

A single "L" shaped antenna with 5 Km long arms would cost approximately $23M. A possibly unnecessary expense in the present above-ground design is the thermal cover for the antenna which constitutes approximately $6M of the total cost of one antenna. Iteration on the costing and the design will be discussed in the section on the work proposed for the next year.

We have studied a variety of the optical engineering problems in the antenna analytically in the past year. We have completed a sensitivity study of the Fabry-Perot and delay line systems. Both systems are viable candidates for the antenna optics, neither however is trouble-free. The choice here will rest on laboratory experience in the prototype antennas. At present, we still favor delay lines but this is in part due to familiarity and the success of the Munich group.

A thorough study of fiber optic antennas was carried out. There are now clear arguments why a fiber optic system will not function adequately as a gravity antenna. The thermal noise in a fiber is eight orders of magnitude larger in amplitude than our strain specifications. Furthermore, the power handling capability of long fibers is limited by Brillouin and Raman scattering processes. The maximum power levels are 100 to 1,000 times lower than the optical power required for gravity wave research.

During the course of the past year, we have generated the outline of the study report (Appendix 1). Some of the issues in it have been addressed by last year's work.

RESEARCH PLAN OF THE CURRENT YEAR

Prototype Antenna

In this and the coming year we intend to measure the noise spectra of the completed instrument and identify the driving noise sources by a set of cross-correlation studies. The cross-correlations will be carried out between the antenna signals and the signals from a group of other sensors designed to measure the anticipated driving noise sources. In particular, we intend to measure the correlation to ground noise, acoustic noise, electric and magnetic field fluctuations and laser amplitude and frequency fluctuations.

Our goal is to demonstrate a displacement sensitivity of 10^{-16} cm/Hz$^{1/2}$ in quiet bands in the instrument where the noise is dominated by the photon shot noise at the detector. Achieving this goal will require a second iteration of some of the optics in the prototype, once we are satisfied that we understand its performance. In particular, we will need to inject higher laser power into the interferometer. This will require a change in the electro-optic modulators, mirrors, and mirror coatings now installed in the instrument.

The demonstration of the displacement sensitivity is essential for the credibility of the large antenna concept and therefore remains the highest priority experimental study.

Ground Noise Isolation Research

As indicated in prior proposals and in our publications, a difficult problem in achieving the specified low frequency performance for a large baseline antenna is the isolation of ground noise at the antenna masses. The end masses operate at room temperature, to maintain the thermal noise below specifications at 30 Hz in a 5 Km long antenna, will require $\frac{Qm}{\nu_0}$ products in excess of 10^9. Here Q and ν_0 are the quality factor and resonance frequency of the suspension and m is the antenna mass. If we avoid exotic high Q materials and very long period suspension, it is reasonable to expect that the end masses of a large baseline antenna will have a mass of the order of one ton. We require 120 db of broad band ground noise isolation at 30 Hz at a quiet site to achieve these specifications. This requirement drives both the mass of the inertial reference element as well as the loop gain in an active vibration isolation system. Our experience with the prototype one-dimensional isolation system indicates that we will have to cascade isolation stages as the requisite loop gain cannot be achieved in a single stage due to the finite stiffness of the structural members of the suspension. Furthermore, for reasons of the thermal noise, the mass of the inertial reference element needs to be in the neighborhood of a ton. As a consequence, it makes good sense to use the antenna mass itself as the primary inertial reference in a set of nested active isolation stages.

We are presently working on the analytic solution for this concept. As a prelude to building a full size large antenna end station, we would like to implement part of the concept in the laboratory this year. We intend to support a one tone aluminum mass in air on a 2 sec. suspension. If limited only by air friction, the Q could be of the order of 10^7. The supporting structure is a pair of nested massive frames, one supported by the other, with the mass hanging from the inner one. The motion of the inner frame is servoed to a null by using the central mass as reference. The displacement transducer is a differential X band microwave cavity sensed by a Ga As FET amplifier. The displacement sensitivity at this stage is required to be 10^{-14}cm/$Hz^{1/2}$. A pair of linear motors, X and Y, apply forces between inner frames and the ground to achieve this null. The outer frame motion is sensed with respect to the mass by capacitive displacement transducers of the type we are now using at a sensitivity of 10^{-11}cm/$Hz^{1/2}$. The outer frame is servoed to a null relative to the mass by linear motors between the outer frame and the ground.

The proposed system will scale the vacuum enclosure for the antenna end station, and is a test bed for the actual servo designs to be used in the large antenna.

HIGH OPTICAL POWER ELECTRO-OPTIC MODULATORS AND FIBER COUPLERS

In the course of our large antennas study, it has become clear that some of the techniques being used in the optical systems of the delay line in the prototype antenna will not scale directly to application in the large antenna where we intend to use 100 watts of optical power rather than 1. There are two special areas which are troublesome. Single mode polarization preserving fibers are used effectively as laser spatial mode filters to couple the laser to the interferometer in the prototype. The damage threshhold in these fibers occur at intensities close to 10^8 watts/cm^2, the intensity of one watt propagating in a typical commercially available single mode fiber. In order to inject 100 watts into an interferometer, one could use a fiber bundle with separate amplitude stabilization servoes for each fiber. However, it would be considerably easier if one could use larger diameter single mode fibers. The fiber mode dimension is determined by the index difference between core and cladding in index-stepped fibers.

The intensity in the fiber scales as $P\Delta n$, where P is the propagating power and Δn is the difference in index of core and cladding. At present, the fibers we are using have a $\Delta n \sim 10^{-2}$. We would like to test large diameter fibers with $\Delta n \sim 10^{-4}$. Fibers of this nature can be made as special items by Fiberguide Industries Inc. as well as other fiber manufacturers using Boron doping techniques in Borosilicate fibers.

A second problem area is the availability of Pockel's cell phase modulators able to handle the required intensities. The cells must have excellent homogeneity, high transmission in the visible, small piezo electric constants for the direction of the modulating fields and small dielectric loss tangents at the modulation frequencies. The material being used in the prototype is AD*P which satisfies all the above requirements short of the power handling capability. Here, as with the fibers, it is possible to make a matrix stack of Pockel cells with electrodes running along the beam propagation direction in an expanded beam which is recollimated after modulation. There are however newer materials with higher power handling capability. In particular, LiTaO3 is now grown by the Crystal Technology Corp. which may satisfy all the requirements. LiTaO3 has a large non-linear polarizability, however, which will cause the index of the material to be intensity dependent and thereby could produce wave-front distortions. Nevertheless, it is an interesting and possibly extremely useful material. In the course of this year we would like to test Pockel's cell of LiTaO3 and other candidate materials.

FAST PRESSURE FLUCTUATION MEASUREMENTS IN A METAL VACUUM SYSTEM

The average pressure in the evacuated pipes of the large gravitational antenna is set by the condition, that pressure fluctuations of a purely Poisson nature that occur in the laser beam should not produce phase changes of the light larger than those inferred by the photon shot noise. This condition sets the average pressure in the vacuum enclosure of the interferometer arms to 10^{-5}mm Hg or less. A worry that has beset both MIT and CalTech is the possibility that the outgasing by tubing walls is burst-like rather than steady. If this is so, it may be material and temperature dependent. There is no good data on the power spectrum of the outgasing in vacuum system and as a consequence it must be measured. This doesn't appear to be a very difficult experiment and could be handled as a senior thesis topic in physics. The proposed experiment is to evacuate a 5 foot section of 12" diam. aluminum and stainless steel tubing to a pressure of 10^{-7}mm Hg with roughing pumps and then with Zeolite clad liquid nitrogen Cryo pumps. An ion gauge of the Bayard-Alpert design is constructed coaxial extending the full length of the tube. The ion collector runs along the center of the tube, surrounded by a concentric spiral stainless steel grid. The electron source is a single wire of tungsten running parallel to the cylinder axis along the outside of the grid. The measurement will be to determine the power spectrum of the ratio of the ion current to the electron current.

LARGE BASELINE ANTENNA STUDY

The near term aim of the study is to produce a partial report based on the outline in Appendix I by October of 1983, in time for presentation to the NSF advisory panel. In this partial report we will emphasize those aspects of the project which drive the costs: the site, installation and construction. The completed study will be ready in the spring of 1984. Stone and Webster is at present (March 1983), making a study of available sites both above and below the ground. This study will be done by July.

Following the site study, during the summer of 1983, they and we will carry out iterations of the cost estimates made in December 1982. The iterations will include site specific factors such as: whether a cover is needed for the antenna, or if power and water have to be brought to the site. We will explore once again the tradeoff between above ground and trenched subsurface construction. This issue now appears to be a major decision point in determining costs of an antenna system.

We will refine the cost estimates for the instrumentation, in particular, with the help of Arthur D. Little, make a better cost estimate of the antenna end station vacuum system. Before this can be completed, however, we must have a more complete conceptualization of the active ground noise isolation system. Work leading to this is now in progress.

After October 1983 we will continue the study of various important engineering problems that must be solved to build a large antenna but that are expected to have only minimal cost impact on the project. These are primarily problems in the optical system:

1) A survey of commercial lasers in the visible and near IR to find candidates other than the Argon Ion laser which could provide 100 watts CW. Chemical lasers operating at 1 KW CW at 1 micron will be investigated in this survey.

2) Investigate the techniques of integrated optics as a means of making compact and stable structures that combine laser amplitude stabilization, phase noise modulators and fiber optic couplers into a single unit.

3) Study the normal modes and thermal noise in large mirrors and their associated mounts.

4) In conjunction with the experimental work on the prototype, study the scattering properties of high reflectivity mirror coatings.

Appendix 1

OUTLINE OF REPORT

1) REVIEW OF ASTROPHYSICAL SOURCES

   1a) Impulsive sources
   Amplitude, Power Spectra, Rate, Pulse shapes

   1b) Periodic sources
   Amplitude, Spectral width, Harmonic content

   1c) Stochastic background
   Power spectra

2) DETECTION CRITERIA

   2a) Impulsive sources
   Confidence limit vs. single antenna noise (Gaussian),
   Confidence limit vs. single antenna noise (Non-Gaussian),
   Gaussian + Parametrized tail;
   Improvement with matched filters - Templates,
   Increase of confidence limit with multiple antenna,
   cross correllation Gaussian and non-Gaussian cases.

   2b) Periodic Sources
   Bandwidth reduction methods, fft vs. continuous fourier transform
   gain in antenna cross correllation
   Gaussian vs. non-Gaussian cases
   optical or radio cross correllation

   2c) Stochastic background by cross correllation
   optimal bandwidth if noise spectra are known,
   multiple vs. 2 antennas

3) STRATEGIES WITH MULTIPLE ANTENNAS
   Bars - interferometers
   Interferometers of varying storage time
   Gains in detecting both polarizations of wave
   Multiple antennas at a single site - different geometries, and different lengths in the same vacuum enclosure

   Large antenna vs. several smaller antenna
   Confidence limits of detection vs. number of antennas vs. noise in a single antenna

   Antenna optimization vs. search frequency,
   Is longer always better?
   Judgement on low frequency search validity

4) NOISE IN INTERFEROMETRIC ANTENNAS

4a) Transducer noise

- 4a1) Shot noise limit with wavefront distortion and scattering background
- 4a2) Effect of laser frequency instabilities Beam translation and angular fluctuations
- 4a3) Amplitude noise - Plasma oscillations, acoustic oscillations
- 4a4) Discussion of control of these fluctuations

4b) Seismic noise, wind noise, acoustic noise

- 4b1) Estimates of driving spectra, site dependance
- 4b2) Response to seismic noise in instrument
  - 4b21) Direct motions - correllations of length
  - 4b22) Second order motions - Cross coupling
  - 4b23) Effects on the interferometry
    - a) Misalignment of interferometer
    - b) Time dependent apodization at small openings
    - c) Fluctuating diffraction contribution at edges
    - d) Modulation of scattering
- 4b3) Methods of reducing seismic noise
  - 4b31) Passive systems
    - a) Isolation available, frequency bands, Multiple and single systems
  - 4b32) Active systems
    - a) Properties of reference elements
    - b) Servo designs
    - c) Suspension designs
    - d) Single and nested stages

4b33) Combined active and passive stages

4b34) Regression techniques

a) Measurement of seismic motions
b) Knowledge of system transfer functions

4c) Gravity gradient noise

4c1) "stationary" power spectra - correllation lengths
Density fluctuations earth and atmosphere

4c2) Transient noise

a) Large events, probability distribution
b) anthropogenic sources

4d) Thermal noise

4d1) Suspension noise - Nyquist noise
4d2) Thermal noise in optical components
Mirror mode excitation
Thermal density fluctuations in optical modulators
4d3) Techniques for reducing thermal noise
Question of high Q (narrow) vs. low Q (broad)
Active control of Q with noise free damping
Stiff elements, larger masses
Cooling?

4e) Propagation noise

4e1) Naive vacuum model
4e2) Outgassing model, estimates of pressure changes
and parameters affecting time constants and
power spectra

4f) Magnetic and electric field noise

4f1) Power spectra of B and E fluctuations in vacuum
systems

4f2) Interaction of masses with B and E fluctuations
Ferrous and ferric impurity limits,
Paramagnetic and diamagnetic susceptibilities
Patch effect and charging of insulating surfaces

4f3) Shielding requirements
    μ metal, superconducting shields?
    Screening of mirrors - dielectric vs. metal mirrors

4f4) Regression of B and E fluctuations by internal sensors and measurement of mass transfer functions

4g) Particle noise - Cosmic rays and natural radioactivity

4g1) Event spectrum
4g2) Estimates of noise in positions of masses due to event spectrum

4h) Radiometer effects and other surface heating phenomena

4h1) Typical operating temperatures and thermal gradients in the end stations due to laser heating and convection outside

4h2) Vacuum requirements in the end stations

5) SPECIAL TOPICS

5ST1) Why not a fiber optic interferometer

5ST11) Thermal noise in propagation
5ST12) Pressure and strain sensitivity
    Requirements for acoustic and seismic isolation
5ST13) Power limits and internal losses
5ST14) Magnetic sensitivity
5ST15) Compensating schemes

5ST2) Description of alternative optical schemes
    Fabry Perot and wide band

ST21) Present state of performance
ST22) Potential and hazards of both systems
    Displacement sensitivity vs. power
    Effect of scattered light
    Recycling methods
    Complexity, # of servo system
    Matching requirements
    Injection requirements
    Frequency stability requirements
    Thermal noise in optic modulators
    Effect of wave front distortion
    Alignment sensitivity
    Are there criteria to choose one or the other?

5ST3) Optical engineering considerations common to both systems

- 5ST31) Mirrors
  - Figure control
  - Mounting techniques to maintain internal Q and mirror figure. Mirror rigidity requirements
  - Power constraints on coatings

- 5ST32) Scattering
  - Small angle scattering vs. mirror coating and figure distortions -
  - Comparison of dielectric and metallic reflector scattering properties
  - Effect of scattering (diffraction) by tube walls

- 5ST33) Laser properties
  - Optimization of $\lambda/\rho\delta$
  - Efficiency - Optical power out/electrical power in
  - Intrinsic amplitude noise
  - Mean life before failure

- 5ST34) Electro-optic modulators
  - Homogenity requirements - scattering and position dependent phase shifts
  - Size and laser intensity constraints
  - Thermal stability in vacuum
  - Bandwidth limits

- 5ST35) Photo detectors
  - Quantum efficiency
  - Intensity and power limits
  - Homogeneity of active area
  - Bandwidths

6) LARGE ANTENNA PARAMETERS INDEPENDENT OF SPECIFIC INTERNAL DESIGN

6a) Site selection
criteria - availability, seismicity, extrinsic noise, thermal environment, water fluctuations, long term stability, access, ease of construction, facilities available at site, possible future developments around site

- 611) Analysis of some sample sites VLA, New Mexico
  Sandia, New Mexico

- 612) Survey of old military bases, abandoned salt mines

6b) Vacuum system

- 620) Time constant, ultimate pressure
- 621) Tubing material
- 622) Choice of pumps
- 623) Valving strategy
- 624) Welding techniques
- 625) Cleaning and outgassing
- 626) Power requirements for pumps
- 627) End station vacuum
- 628) Alignment techniques active/passive
- 629) Expansion joints
- 6210) Cost scaling laws as a function of tubing diameter, antenna length and pressure specification. Separation of fixed and length dependent costs

6c) Construction
Strongly modulated by the properties of the site, in particular if site has been developed or not.
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- 630) Site preparation
- 631) Number of buildings required
- 632) Tubing piers and alignment mounts
- 633) External housing of vacuum pipe
- 634) End station construction
- 635) Access roads
- 636) Power requirements
- 637) Electrical cabling and instrumentation ports
- 638) Cooling requirements
- 639) Temperature control of antenna
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- 641) Cost relations, fixed and length dependent factors

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- 71) Laser to be used
- 72) Mirrors, mirror coating
- 73) Mirror mounts and end masses
- 74) Vibration isolation system - suspension design
- 75) Electro optic modulators and source of them
- 76) Servo calculation - forcers and optical controllers
- 77) Instrumentation requirements - Parameters to be measured with interferometer output
- 78) Computer requirements on site

Appendix 2

OBSERVATION OF SPATIAL VARIATIONS IN THE RESONANCE FREQUENCY OF AN OPTICAL RESONATOR

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ABSTRACT

The observation of a dependence of the measured resonance frequency of an optical cavity on the size and position of the detector is reported and attributed to the presence of higher order transverse modes in the cavity. This effect, which is due to the nonorthogonality of these modes when averaged over a limited aperture or an inhomogeneous detector surface, has been carefully studied. The results of our calculations are in good agreement with experimental observations. Methods of minimizing such frequency pulling effects are suggested.

Appendix 3

THE TERRESTRIAL GRAVITATIONAL NOISE
ON A GRAVITATIONAL WAVE ANTENNA

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Introduction

A new generation of interferometric antennas for the detection of gravitational radiation of cosmic sources is being planned. Detection of gravitational waves is performed by measuring the relative displacements of several nearly-free masses which carry the mirrors defining a Michelson interferometer. The measured quantity is the difference (as a function of time) in the lengths of the two orthogonal arms of the interferometer. In principle, this form of antenna can be sensitive down to quite low frequencies (in contrast to bar antennas, which are high-Q resonators with natural frequencies of order 1 kHz). In practice, various noise sources will limit the useful bandpass. One form of noise is random gravitational forces. This is a particularly important form of noise, since gravitational forces can not be shielded, even in principle.

Sources of random gravitational forces can be grouped into two categories. One sort is fluctuations in the density of a medium (air or earth) surrounding the antenna. The other kind is the motion of isolated massive bodies in the vicinity of the antenna. (These are not completely distinct categories -- an airplane generates sound, so both sorts of sources are present.)

Appendix 4

AN ACTIVE VIBRATION ISOLATION SYSTEM

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Introduction

A Michelson interferometer with mirrors mounted on free masses is an inherently broad-band antenna for gravitational waves. This is a potential advantage over bar antennas, which because of their resonant character are only sensitive over a narrow range of frequencies. Any practical terrestrial antenna must be supported against the earth's gravitation and thus be mechanically coupled to the surface of the earth. This means that the interferometer end masses are subject to forces due to seismic background vibrations. The power spectrum of earth vibrations is a steeply falling function of frequency (see Figure 1). So for measurements near 1 kHz or higher, simple passive isolation techniques (such as spring or pendulum suspensions) suffice to attenuate the seismic noise. However, the attenuation from a passive isolator is small near its resonant frequency, and resonant frequencies much below 1 Hz make an oscillator impractically close to astability. For these reasons simple passive seismic isolation is wholly ineffective for frequencies of a few hundred Hertz or below.

An active (servo-controlled) isolation system holds the promise for solving the low frequency isolation problem. An accelerometer measures motion of a platform with respect to an inertial frame of reference. The error signal from the accelerometer, suitably filtered, drives a linear actuator which applies a force to the test mass. The stability conditions for this null servo are most easily satisfied when the loop gain (i.e., seismic attenuation) is falling as a function of frequency. This is what makes an active system so well-matched to the requirements for low frequency seismic isolation.

We have constructed a one-dimensional model of such an active isolation system. We have achieved isolation of more than 60 dB (three orders of magnitude in amplitude) at low frequencies. In a band between 3 Hz and 8 Hz, this gain is sufficient to bring the motion of the platform within a factor of 2 of the minimum motion allowed by the Brownian motion of the sensing mass of the accelerometer. In this band, the closed-loop acceleration spectral density is $1.5 * 10^{-6}$ $\mathrm{cm/sec^2 Hz^{1/2}}$.