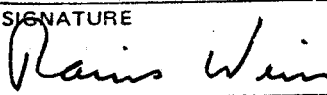


APPENDIX I

PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION
Cover Page

FOR CONSIDERATION BY NSF ORGANIZATIONAL UNIT (Indicate the most specific unit known, i.e. program, division, etc.) Physics ATT: Dr. Richard A. Isaacson		IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? Yes ___ No X ; IF YES, LIST ACRONYM(S):	
PROGRAM ANNOUNCEMENT/SOLICITATION NO.: Proposal ID# PHY-8109581		CLOSING DATE (IF ANY):	
NAME OF SUBMITTING ORGANIZATION TO WHICH AWARD SHOULD BE MADE (INCLUDE BRANCH/CAMPUS/OTHER COMPONENTS): Massachusetts Institute of Technology Physics Department			
ADDRESS OF ORGANIZATION (INCLUDE ZIP CODE) 77 Massachusetts Avenue Cambridge, MA 02139			
TITLE OF PROPOSED PROJECT Interferometric Broad Band Gravitational Antenna			
REQUESTED AMOUNT \$498,710	PROPOSED DURATION one year	DESIRED STARTING DATE July 1, 1983	
PI/PD DEPARTMENT Physics		PI/PD ORGANIZATION	PI/PD PHONE NO. 253-4824
PI/PD NAME Rainer Weiss 128-26-6401	SOCIAL SECURITY NO.* 128-26-6401	DATE OF HIGHEST DEGREE ACHIEVED Ph.D. 1962	MALE* X
ADDITIONAL PI/PD & SIGNATURE Paul Linsay	285-42-0128	Ph.D. 1976	X
ADDITIONAL PI/PD & SIGNATURE Peter Saulson	213-46-3979	Ph.D. 1981	X
ADDITIONAL PI/PD & SIGNATURE			
ADDITIONAL PI/PD & SIGNATURE			
FOR RENEWAL OR CONTINUING AWARD REQUEST, LIST PREVIOUS AWARD NO.: PHY-8109581		IF SUBMITTING ORGANIZATION IS A SMALL BUSINESS CONCERN, CHECK HERE <input type="checkbox"/> (See CFR Title 13, Part 121 for Definitions)	
* Submission of SSN and other personal data is voluntary and will not affect the organization's eligibility for an award. However, they are an integral part of the NSF information system and assist in processing proposals. SSN solicited under NSF Act of 1950, as amended.			
CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW:			
<input type="checkbox"/> Animal Welfare	<input type="checkbox"/> Human Subjects	<input type="checkbox"/> National Environmental Policy Act	
<input type="checkbox"/> Endangered Species	<input type="checkbox"/> Marine Mammal Protection	<input type="checkbox"/> Research Involving Recombinant DNA Molecules	
<input type="checkbox"/> Historical Sites	<input type="checkbox"/> Pollution Control	<input type="checkbox"/> Proprietary and Privileged Information	
PRINCIPAL INVESTIGATOR/ PROJECT DIRECTOR	AUTHORIZED ORGANIZATIONAL REP.	OTHER ENDORSEMENT (optional)	
NAME Rainer Weiss	NAME	NAME	
SIGNATURE 	SIGNATURE	SIGNATURE	
TITLE Professor Physics	TITLE	TITLE	
DATE April 7, 1983	DATE	DATE	

NOTICE OF RESEARCH PROJECT
SCIENCE INFORMATION EXCHANGE
SMITHSONIAN INSTITUTION
NATIONAL SCIENCE FOUNDATION
PROJECT SUMMARY

SIE PROJECT NO.
NSF AWARD NO.

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

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

Massachusetts Institute of Technology

ADDRESS (INCLUDE DEPARTMENT)

Department of Physics
77 Massachusetts Avenue
Cambridge, MA 02139

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.

- 1. Proposal Folder
- 2. Program Suspense
- 3. Division of Grants & Contracts
- 4. Science Information Exchange
- 5. Principal Investigator
- 6. Off. of Govt. & Pub. Progs.

SEE INSTRUCTIONS ON REVERSE BEFORE COMPLETING)

SUMMARY PROPOSAL BUDGET

FOR NSF USE ONLY

ORGANIZATION MIT Physics Dept., Cambridge, MA 02139	PROPOSAL NO. 	DURATION (MONTHS) <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 50%;">Proposed</td> <td style="width: 50%;">Granted</td> </tr> <tr> <td> </td> <td> </td> </tr> </table>	Proposed	Granted		
Proposed	Granted					
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Rainer Weiss	AWARD NO. 					

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	NSF FUNDED PERSON-MOS.			FUNDS REQUESTED BY PROPOSER	FUNDS GRANTED BY NSF (IF DIFFERENT)
	CAL.	ACAD.	SUMR.		
1. Rainer Weiss, P.I.		1	1	\$ 10,906	\$
2. Paul S. Linsay, Co-P.I.	12			30,000	
3. Peter Saulson, Participating Scientist	12			22,000	
4. Shaoul Ezekiel, Faculty Associate		1/2		2,310	
5. (2) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)	24			48,780	
6. (6) TOTAL SENIOR PERSONNEL (1-5)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. () POST DOCTORAL ASSOCIATES					
2. () OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (3) GRADUATE STUDENTS					
4. () UNDERGRADUATE STUDENTS					
5. () SECRETARIAL-CLERICAL					
6. () OTHER					
TOTAL SALARIES AND WAGES (A+B)				136,856	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) 38% of S&W				52,005	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				188,861	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING \$1,000; ITEMS OVER \$10,000 REQUIRE CERTIFICATION)					
TOTAL PERMANENT EQUIPMENT				111,350	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				2,000	
2. FOREIGN				1,000	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS \$ _____					
2. TRAVEL _____					
3. SUBSISTENCE _____					
4. OTHER _____					
TOTAL PARTICIPANT COSTS					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				6,000	
2. PUBLICATION COSTS/PAGE CHARGES				1,500	
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS				70,000	
6. OTHER				1,500	
TOTAL OTHER DIRECT COSTS					
H. TOTAL DIRECT COSTS (A THROUGH G)				382,211	
I. INDIRECT COSTS (SPECIFY)					
58% on all but equipment and ongoing subcontracts				116,499	
TOTAL INDIRECT COSTS				498,710	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				0	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS GPM 252 AND 253)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				\$	\$

PI/PD TYPED NAME & SIGNATURE*	DATE*	FOR NSF USE ONLY		
		INDIRECT COST RATE VERIFICATION		
		Date Checked	Date of Rate Sheet	Initials - DGC
INST. REP. TYPED NAME & SIGNATURE*	DATE	Program		

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R. Weiss.....	
P. Linsay.....	
P. Saulson.....	
S. Ezekiel.....	

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 $10^{-23}/\text{Hz}^{1/2}$ at 1 KHz rising to $10^{-21}/\text{Hz}^{1/2}$ 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/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 outgassing 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 theodolite, and an

enclosure surrounding the vacuum tubes would be used to temperature regulate to $\pm 10^{\circ}\text{C}$. 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:

	<u>Fixed</u>	<u>\$/Km</u>
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 $10^{-16} \text{ cm}/\text{Hz}^{1/2}$ 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 $\frac{Qm}{\mu_0}$ products in excess of 10^9 . Here Q and μ_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 threshold in these fibers occur at intensities close to 10^8 watts/cm², 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 Ins. 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.

BUDGET - RESEARCH GRANT RENEWAL

July 1, 1983 - June 30, 1984

A. Salaries and Wages

1. Senior Personnel

a) Principal Investigator R. Weiss (11% - 9 mos., 100% - 1 mo.)	\$ 10,906
b) Co-investigator P. Linsay (100% - 12 mos.)	30,000
c) Participating Scientist P. Saulson (100% - 12 mos.)	22,000

2. Other Personnel

a) Engineer R. Benford (100% - 12 mos.)	30,780
b) Technical Physicist D. Shoemaker (100% - 12 mos.)	18,000

3. Graduate Students

a) Antenna D. Dewey (100% - 12 mos.)	7,620
b) Antenna and High Power Optics J. Livas (100% - 12 mos.)	7,620
c) Ground Noise Isolation	7,620

4. Faculty Associate S. Ezekiel (5% - 9 mos.)	2,310
--	-------

TOTAL SALARIES AND WAGES \$136,856

B. Fringe Benefits (38% of S&W) 52,005
C. Total Salaries and Wages and F.B. \$188,861

D. Industrial Consultants	
1. Stone and Webster	60,000
2. A.D. Little	10,000
E. Equipment	111,350
F. Expendable Supplies and Services	6,000
G. Travel	3,000
H. Publishing Costs	1,500
I. Secretarial Help (Agency)	1,500
J. Overhead (58%)	116,499
K. Total Costs	498,710

1983-1984 EQUIPMENT

Optics

High Power Argon Ion Laser and Power Supply

45,000

Coherent Innova 20
Model 424 Etalon

1,500

Replacement Tube for Spectra-Physics
Model 165-03 Argon Ion Laser

6,500

Pockel Cell Phase Modulator Crystals

LiTaO3 Crystal Technology

5,000

AD*P Inrad Corp.

3,500

CD*As Quantum Electronics Corp.

3,000

Mirrors and Coatings for Prototype

Valtec Corp. and Litton Industries

4,000

Large Diameter Single Mode Polarization

Preserving Optical Fiber (Development Item)

Corning Glass Corp.

or Andrew Corp.

or Fiberoptic Industries Inc.

4,000

Data Processing Equipment

VT 125 Video Terminal with Graphics
(includes MIT discount)

2,700

DT 2782 16 Channel, 12 Bit ADC, 135 KHz

2 x \$1,800 each

3,600

BA-11 NE/JB LSI 11 Expander Box

\$2,000
10% disc. 200
\$1,800

1,800

DT 2766 4 Channel, 12 Bit DAC

2 x \$800 each

1,600

BCVIB-10/JB LSI Bus. Expansion Cable,

350

LA 50 Printer

850

Equipment for Ground Noise Isolation

GaAs FET Amplifier Avantek	\$ 2,500
Gunn Oscillator Diode and Stabilized Power Supply to Drive Oscillator	\$ 2,500
Four Linear Motors (Surplus Disk Head Drives)	1,600
X Band μ Wave Plumbing	800
Aluminum Structural Equipment	
Industrial Aluminum Corp.	4,000
Electronic Parts for Vibration Isolation Equipment	2,000

Equipment for Vacuum Fluctuation Experiment

Vacuum Plumbing	1,000
Flanges - Huntington Corp.	300
Cryo Pumps - Veeco Corp.	1,400
Electronics for Vacuum Fluctuation Experiment	1,000

General Purpose Equipment

Tektronix Oscilloscope		
7704A Mainframe		4,220
2: 7A26 Amplifier	\$1,745	3,490
7B80 Time Base	1,190	
Option 02, X-7	<u>100</u>	
	\$1,290	1,290
7B85 Delaying Time Base		1,425
Tek Lab Cart Model 3		425
TOTAL EQUIPMENT		\$111,350

Expendable Materials and Services

1/2 Computer Service Contract	\$ 2,000
Telephone	1,500
Computer Disks, Tapes, Paper	1,500
Machine Shop Time (50 hrs)	<u>1,000</u>
TOTAL MATERIALS AND SERVICES	\$ 6,000

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 correlation Gaussian and non-Gaussian cases.
- 2b) Periodic Sources
Bandwidth reduction methods, fft vs. continuous
fourier transform
gain in antenna cross correlation
Gaussian vs. non-Gaussian cases
optical or radio cross correlation
- 2c) Stochastic background by cross correlation
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 dependence

4b2) Response to seismic noise in instrument

4b21) Direct motions - correlations 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 - correlation 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

Homogeneity 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.
Critically dependent on above or below ground construction.

- 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
- 640) safety and fire control
- 641) Cost relations, fixed and length dependent factors

7) A SAMPLE DESIGN AND COST

- 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

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.

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.)

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 instability. 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 $1.5 \times 10^{-6} \text{ cm/sec}^2 \text{ Hz}^{1/2}$.

OTHER SOURCES OF SUPPORT OF FACULTY ON THIS PROPOSAL

R. Weiss

NASA	"Astronomy in the Region Between 1 mm and 0.1 mm Wavelengths"			
		FY 1983	\$90,000	5% Salary
NASA	Phase B Study of COBE (Cosmic Background Explorer Satellite)			
		FY 1983	\$43,000	17% Salary
			(est.)	

S. Ezekiel

NSF	"Atom-Field Interactions"		\$135,000	10% Salary
		FY 1983	(Pending)	
Air Force/Rome Development Ct.	"Micro-wave Frequency Standards Using Lasers"			
		FY 1983	\$30,000	10% Salary
			(Pending)	
Joint Services Electronics Program (RLE-MIT)				
		FY 1983	\$90,000	15% Salary
AFOSR	"Experimental and Theoretical Investigations in Fiber Optic Rotation Sensors"			
		FY 1983	\$125,000	10% Salary
			(Pending	
			New	
			Proposal)	

Resume

PAUL S. LINSAY

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RESEARCH:

- 1979- Experimental General Relativity: Design and construction of a free mass Michaelson interferometer to detect gravitational radiation. Current work centers on a prototype antenna with 1.5 meter arms, with a theoretical strain sensitivity of $10^{-10}/\text{Hz}^{1/2}$. The work has included design and construction of radio frequency servomechanisms, high vacuum systems, and optics. We are also in the process of designing a very large antenna with 10 km arms.
- 1981- Non-linear Dynamics: Experimental work to study the transitions to chaos and the nature of chaotic states in nonlinear systems. My present research is on chaotic behavior in driven semiconductor oscillators.
- 1976- High Energy Physics, Neutrino Scattering: A massive experiment to study the nucleon structure functions by measuring the differential and total neutrino scattering cross sections. My responsibilities included design and construction of large area scintillation counters, fast electronics, beam design, and data analysis.
- 1970- High Energy Physics, Kaon Physics: A measurement of the rare decay $K_0 \rightarrow \mu^+ \mu^-$. An earlier experiment had placed an upper bound on this decay that was in conflict with unitarity, quantum electrodynamics, and the measured rate for the process $K_0 \rightarrow \gamma \gamma$. We measured the branching ratio to be 8.4×10^{-9} , in agreement with theory. My responsibilities included design, construction, and operation of the spark chamber system, digital electronics, computer software to operate the experiment, and data analysis.

EMPLOYMENT:

- 1979- Research Scientist, M.I.T.
1976- Research Fellow in Physics, California Institute of Technology
1979

EDUCATION:

- 1976 Ph.D., Physics, The University of Chicago
1970 M.S., Physics, The University of Chicago
1969 B.S., Mathematics, M.I.T.

GRANTS:

- 1982- Alfred P. Sloan Foundation: Studies in nonlinear dynamics; \$15,000.
- 1981- National Science Foundation: Broadband Interferometric Laser Gravity Antenna; Three year grant \$1,282,000. Co-investigator. Prof. Rainer Weiss, M.I.T., principle investigator.
1984

Publications:

NONLINEAR DYNAMICS:

A Driven Semiconductor Oscillator with a Self-replicating Attractor, S.D. Brorson, D. Dewey, and P.S. Linsay, (submitted for publication)

Period Doubling and Chaotic Behavior in a Driven Anharmonic Oscillator, P.S. Linsay, Physical Review Letters 47, 1349(1981)

GENERAL RELATIVITY, INTERFEROMETRIC GRAVITY ANTENNA:

A Low Noise RF Capacitance Bridge, P.S. Linsay, and D.H. Shoemaker Reviews of Scientific Instruments 1014, 53(1982)

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M.J. Shochet, P.S. Linsay, C. Grosso-Pilcher, H.J. Frisch, R. Devoe, J.W. Cronin, and D.R. Moffett, Physical Review D19, 1965(1979)

Measurement of the Branching Ratio $(K_L^0 \rightarrow \pi^+ \pi^-) / (K_L^0 \rightarrow \text{all})$
R. Devoe, J.W. Cronin, H.J. Frisch, C. Grosso-Pilcher, P. Linsay, M.J. Shochet, and D.R. Moffett, Physical Review D16, 565(1977)

Measurement of the Decay rate for the Rare Process $K_L^0 \rightarrow \mu^+ \mu^-$
M.J. Shochet, P.S. Linsay, C. Grosso-Pilcher, H.J. Frisch, R. Devoe, J.W. Cronin, and D.R. Moffett, Physical Review Letters, 39, 59(1977)

BIOGRAPHICAL SKETCH

Shaoul Ezekiel

Date of Birth: July 20, 1935

Title: Professor

Citizenship: U.S.A.

Education

Imperial College of Science, London, England, Electrical Engineering -
B.Sc., June, 1957.

Massachusetts Institute of Technology, Aeronautics and Astronautics -
S.M., June, 1964.

Massachusetts Institute of Technology, Instrumentation - Sc.D. June, 1968.

Research and/or Professional Experience

Development Engineer - Carrier Communication & Data Handling
General Electric Company, Coventry, England, 1957-1959.

Research & Development Engineer - Flight Simulators, Canadian Aviation
Electronics, Montreal, Canada, 1959-1962.

Research Assistant - M.I.T., 1962-1968.

Instructor - Dept. of Physics, M.I.T., January 1968 - July 1968.

Assistant Professor, Department of Aeronautics and Astronautics, M.I.T.
July 1968 - June 1972.

Associate Professor, Department of Aeronautics and Astronautics, M.I.T.
July 1972-June 1976.

Associate Professor, Department of Aeronautics and Astronautics, and
Electrical Engineering & Computer Science, M.I.T. July 1976 - June 1978.

Professor, Department of Aeronautics and Astronautics, and Electrical
Engineering and Computer Science, July 1978 - present.

Membership in Professional Societies

Fellow of the American Optical Society, Member of the American Physical
Society and the Institute of Electrical and Electronic Engineering

Publications

1. "Sensitive Cryogenic Accelerometer," (with P.K. Chapman), Proceedings of Symposium on Unconventional Inertial Sensors, Polytechnique Institute of Brooklyn, Farmingdale, New York, October 1964.
2. "An Unconventional Inertial Measurement Technique," (with P.K. Chapman), Les Gyroscopes Avances, Memorial de L'Artillerie Francaises, 2⁶ fasc. 1965.
3. "A Superconducting Suspension for a Sensitive Accelerometer," (with P.K. Chapman), Review of Scientific Instruments, January 1965.
4. "Determination of Auxiliary Mirror Curvature in a Michelson-Type Single Longitudinal Mode Resonator," IEEE J. of Quantum Electronics, October 1967.
5. "Laser-Induced Fluorescence in a Molecular Beam of Iodine," (with R. Weiss), Physical Review Letters, 15 January 1968.
6. "Investigations of Coherent Oscillations in an Argon-Ion Laser Plasma Tube," (with D.C. Galehouse, U. Ingard, and T.J. Ryan), Applied Physics Letters, January 1, 1971.
7. "Molecular Beam Stabilized Argon Laser," (with T.J. Ryan, D.G. Youmans, and L.A. Hackel), Applied Physics Letter, 1 October 1972.
8. "High-Resolution Spectroscopy of I₂ Using Laser-Molecular Beam Techniques," (with D.G. Youmans and L.A. Hackel), J. of Applied Physics, May 1973.
9. "Lasers," Optical Engineering, 12, G141, 1973.
10. "Coherence of Laser Light," Optical Engineering, 12, G183, 1973.
11. "Closed Loop, Real Time Holographic Interferometry," (with M.A. Dobbels and E.M. Stolle), Proceedings of Conference on Laser Engineering and Applications, May 1973.
12. "Micro-Angstrom Spectroscopy," (with L.A. Hackel and D.G. Youmans), J. Optical Society of America, 63, 907, 1973.
13. "Molecular Beam Stabilized Laser," (with L.A. Hackel and D.G. Youmans), Proceedings, 27th Annual Symposium on Frequency Control, U.S. Army Electronics Command, Fort Monmouth, New Jersey, 1973.
14. "Laser Molecular Beam Techniques for High-Resolution Spectroscopy," (with L.A. Hackel and D.G. Youmans), Proceedings of Fourth International Symposium on Molecular Beams, Cannes, France, July 9-12, 1973.

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15. "Long-Term Laser-Frequency Stabilization Using a Molecular Beam Reference," (with D.G. Youmans and L.A. Hackel), Proceedings of Fourth International Symposium on Molecular Beams, Cannes, France, July 9-12, 1973.
16. "A Study of Vortex Rings Using a Laser Doppler Velocimeter," (with J.P. Sullivan and S.E. Widnall), AIAA Journal, October 1973.
17. "Laser Molecular Beam Measurement of Hyperfine Structure in the I₂ Spectrum," (with D.J. Ruben, S.G. Kukolich, L.A. Hackel and D.G. Youmans), Chemical Physics Letters, 1 October 1973.
18. "Jet Stream CW Dye Laser for High-Resolution Spectroscopy," (with R.E. Grove, F.Y. Wu, L.A. Hackel and D.G. Youmans), App. Phys. Letters, 15 October 1973.
19. "High-Resolution Holographic Contour Generation Using a Pulsed Multicolor Ion Laser," (with P. Henshaw), Applied Optics, November 1973.
20. "A Two-Component Laser Doppler Velocimeter for Periodic Flow Fields," (with J.P. Sullivan), J. Phys. E: Scientific Instruments, April 1974.
21. "Molecular Beam Spectroscopy with Argon and Dye Lasers," in Laser Spectroscopy, Eds. Brewer and Mooradian, (Plenum Press), April 1974.
22. "Laser-Frequency Stabilization," Optical Engineering, 13, G5, 1974.
23. "Lasers—Who Needs Them!" Optical Engineering, 13, G53, 1974.
24. "High-Resolution Molecular Beam Spectroscopy," (with L.A. Hackel and D.G. Youmans), J. Optical Society of America, 64, 529, 1974.
25. "Precision Molecular Beam Spectroscopy with Argon and Dye Lasers," (with R.E. Grove, L.A. Hackel, F.Y. Wu and D.G. Youmans), Proceedings of International Quantum Electronics Conference, June 1974.
26. "Dye Lasers," Optical Engineering, 13, G121, 1974.
27. "Frequency-Stable Jet Stream Dye Laser," (with F.Y. Wu and R.E. Grove), J. Optical Society of America, 64, 553, 1974.
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29. "Measurement of Natural Lineshape of I₂ Hyperfine Transitions," (with L.A. Hackel and D.G. Youmans), J. Optical Society of America, 64, 1387, 1974.
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31. "High-Resolution Holographic Contour Generation with White Light Reconstruction," (with P.D. Henshaw), Optics Communications, September 1974.
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33. "Precision Measurement of Hyperfine Structure in I_2 ," (with L.A. Hackel and D.G. Youmans), Proc. of the Society of Photo-Optical Instrumentation Engineers, Vol. 69, "Impact of Lasers in Spectroscopy," August 1974.
34. "Molecular Beam Spectroscopy with Lasers," (Invited Paper), Bull. American Physical Society, Vol. 19, No. 10, p. 1182, November 1974.
35. "The Ring Laser," Optical Engineering 13, G217, 1974.
36. "Frequency Stabilization of a CW Dye Laser," (with R.E. Grove and F.Y. Wu), Optical Engineering 13, 531, 1974.
37. "A New High-Resolution Holographic Contouring Method," (with P.D. Henshaw), Proceedings of the Society of Photo-Optical Instrumentation Engineers, Vol. 51, Coherent Optical Processing, August 1974.
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39. "Observation of Magnetic Octupole and Scalar Spin-Spin Interactions in I_2 Using Laser Spectroscopy," (with R.A. Hackel, K.H. Casleton and S.G. Kukolich), Physical Review Letters, 35, 568, 1975.
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41. "Sensitivity of Multiloop Sagnac Interferometer and Laser Gyroscope," (with S. Balsamo), Laser Focus, October 1975.
42. "Investigation of the Spectrum of Resonance Fluorescence Induced by a Monochromatic Field," (with F.Y. Wu and R.E. Grove), Phys. Rev. Letters 35, 1426, 1975.
43. "The Stress-Strain Behavior of the Corneal Envelope of the Eye. I. Development of a System for Making in vivo Measurements Using Optical Interferometry," (with R.F. Brubaker, L. Chin, L. Young, S.A. Johnson and G.W. Beeler), Experimental Eye Research 21, 37, 1975.

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45. "Molecular Beam Stabilized Multiwatt Argon Lasers," (with L.A. Hackel and R.P. Hackel), Proc. of 2nd Symposium of Frequency Standards and Metrology, Copper Mountain, Colorado, July 1976.
46. "Frequency Distribution of Resonance Fluorescence in an Intense Monochromatic Field," (with F.Y. Wu and R.E. Grove), Proc. of 2nd Symposium on Frequency Standards and Metrology, Copper Mountain, Colorado, July 1976.
47. "High Resolution Tunable Laser Spectroscopy," Proc. SPIE Meeting on Unconventional Spectroscopy, San Diego, California, August 1976.
48. "Measurement of the Spectrum of Resonance Fluorescence from a 2-level Atom in an Intense Monochromatic Field," (with R.E. Grove and F.Y. Wu), Phys. Rev. (A) 15, 227, 1977.
49. "Laser Streak Velocimetry for Two-Dimensional Flows in Gases," (with G.W. Sparks Jr.), AIAA Journal 15, 110, 1977.
50. "Wide-bandwidth Feedback Loop Cuts Jitter in Output of Commercial cw Dye Laser," (with F.Y. Wu), Laser Focus, March 1977.
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53. "Molecular Beam Stabilized Multiwatt Argon Lasers," (with L.A. Hackel and R.P. Hackel), Metrologia, 13, 141, 1977.
54. "Measurement of the Emission and Absorption Spectrum of Strongly Driven Two-Level Atoms," (with F.Y. Wu), Proceedings of Vavilov Conference on Nonlinear Optics, Novosibirsk, USSR, June 1977.
55. "New Techniques for High-Sensitivity, High-Resolution Spectroscopy," Proceedings of Vavilov Conference on Nonlinear Optics, Vovosibirsk, USSR, June 1977.
56. Book Review for Physics Today: "Nonlinear Laser Spectroscopy" by Letokhov & Chebotayev, Springer-Verlag, March 1978.
57. "Two-Level Atoms in an Intense Monochromatic Field: A Review of Recent Experimental Investigations," (with F.Y. Wu), in Multiphoton Processes, Editors: J.H. Eberly and P. Lampronponlos, Wiley, 1978.

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58. "Doppler-Free Stimulated-Emission Spectroscopy and Secondary Frequency Standards Using an Optically Pumped Laser," (with J.B. Koffend, S. Goldstein, R. Bacis and R.W. Field), Phys. Rev. Lett., 9 October 1978.
59. "Passive Cavity Optical Rotation Sensor," (with J.A. Cole, J. Harrison and G. Sanders), in "Laser Inertial Rotation Sensors," Editors S. Ezekiel and G.E. Knausenberger, Society of Photo-Optical Instrumentation Engineering, Vol. 157, 1978.
60. "Techniques for Shot-Noise-Limited Inertial Rotation Measurement Using a Multiturn Fiber Sagnac Interferometer," (with J.L. Davis), in "Laser Inertial Rotation Sensors," Editors: S. Ezekiel and G.E. Knausenberger, Society of Photo-Optical Instrumentation Engineering, Vol. 157, 1978.
61. "Observation of Amplification in a Strongly Driven Two-Level Atomic System at Optical Frequencies," (with F.Y. Wu, M. Ducloy and B.R. Mollow), Phys. Rev. Lett. 38, 1077, 1978.
62. "Observation of Subnatural Linewidths by Two-Step Resonant Scattering in I₂ Vapor," (with R.P. Hackel), Phys. Rev. Lett. 42, 1736, 1979.
63. "Interaction of Two Resonant Laser Fields with a Folded Doppler Broadened System of I₂," (with R.P. Hackel), in Laser Spectroscopy IV, Editors: H. Walther and K.W. Rothe, Springer-Verlag, 1979.
64. "Re-evaluation of the Hyperfine Coupling Constants for B-X Transitions in I₂," (with R.P. Hackel and L.A. Hackel), Phys. Rev. A, 21, 1342, 1980.
65. "Optical Gyroscopes," Proceedings of International Conference on Lasers, Beijing, China, May 1980 (to be published).
66. "High Resolution Spectroscopy of Atoms and Molecules in Monochromatic Optical Fields," Proceedings of International Conference on Lasers, Beijing, China May 1980 (to be published).
67. "Laser Gyroscopes," Proceedings of Sergio Porto Memorial Symposium on Lasers and Applications, Rio de Janeiro, Brazil, June 1980 (to be published by Springer-Verlag).
68. "Absolute Distance Measurements by Variable Wavelength Interferometry," (with F. Bien, M. Camac and J. Caulfield), Applied Optics, 20, 400, 1981.
69. "Influence of Atomic Recoil on Power Broadened Lineshapes in 2-level Atoms," (with P.R. Hemmer and F.Y. Wu), Optics Communication, 38, 105, 1981.
70. "Ultra High-Resolution Spectroscopy and Frequency Standards in the Microwave and Far-Infrared Regions Using Optical Lasers," (with J.E. Thomas, C.C. Leiby, R.H. Picard and C.R. Willis) Opt. Lett. 6, 298, 1981.

Publications (cont'd)

71. "Stabilized Single Frequency Stimulated Brillouin Fiber Ring Laser," (with D.R. Ponikvar) Optics Letters, 6, 398, 1981.
72. "Closed-Loop, Low Noise Fiber-Optic Rotation Sensor," (with J.L. Davis) Optics Letters 6, 505, 1981.
73. "Precision Atomic-Beam Studies of Atom-Field Interactions," (with P.R. Hemmer, B.W. Peuse, F.Y. Wu and J.E. Thomas) Optics Letters, 6, 531, 1981.
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PRINCETON UNIVERSITY, M.A. in Physics

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HARVARD UNIVERSITY, A.B. magna cum laude
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FELLOWSHIPS AND SCHOLARSHIPS

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PUBLICATIONS

- June 15, 1980 P.R. Saulson, B.H. Siebers, Jr., E.D. Loh, and D.T. Wilkinson, "Search for Luminous Halos of Spiral Galaxies," Bulletin of the American Astronomical Society, 12, 490 (paper delivered at the 156th meeting of AAS)
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