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PROGRESS REPORT

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NASA Grant NAGW-1003

Monocrystalline Silicon Gradiometer For Gravity Experiments in Space

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1.-INTRODUCTION

A very important research effort has been made in the last decade in the field of high precision position measurement with laser instrumentation. Significant effort is currently in progress in Munich and Glasgow and at MIT and Caltech with the goal of developing very sensitive kilometre-base-line gravitational radiation antennae. The purpose of our present research effort under NASA grant NAGW-1003 is to develop a space borne gradiometer operating at a sensitivity level of 10^{-4} Eötvös/$\sqrt{Hz}$ using laser measurements of the distance between proof masses over a short base line of order one metre. Two aspects of laser technology make it a promising tool for gradiometry measurements:

1- QUANTUM LIMITED ACCURACY. Laser technology has already reached the level of accuracy where quantum limited measurements can be performed. This aspect of laser instrumentation is discussed in section 3.4.

2- ABSOLUTE DISTANCE MEASUREMENTS. Distances as measured with a laser are referenced to the speed of light which in vacuum is independent of any parameter of the environment. Thus the potential for high accuracy is outstanding since, in principle, no other potentially unstable reference unit, such as a support for proof-mass position sensors, is needed.

2.- ABSTRACT OF FIRST YEAR EFFORT

During our first year effort, the following has been accomplished:

1- The quantum-limit associated with laser instrumentation such as used here for gradiometry measurements has been formulated.

2- We have reviewed the relevant quantum and classical sources of errors in laser measurements and evaluated corresponding laser performance requirements for gradient measurements at the level of 10^{-4} Eötvös /$\sqrt{Hz}$.

3- We have requested and obtained from our physic department a laboratory space for work on this project.

4- We have performed some mechanical quality factor (Q) measurements on simple resonant monocrystalline Silicon suspensions.

5- We have discovered that the use of "zero-derivative" restoring forces to position the gradiometer test-masses will dramatically reduce the gradiometer temperature control requirement.

6- We have discovered a laser beam "side-injection" scheme which permits rejection of common mode accelerations . It also eliminates laser instability problems associated with light reentering the laser. These two properties are very important.

7- The original gradiometer scheme has been modified to make it possible to use zero-derivative restoring forces and side-injection.

8- Some general laboratory instrumentation has been acquired. A helium leak detector transferred from Goddard surplus has been refurbished at minimum cost. An optical table, supports and optical components have been acquired or are on order for a test setup to analyze low-frequency noise in a two-arm laser instrumented gradiometer.

Items 1-8 are discussed in details in sections 3 and 4 of this report. Plans for next year effort are given in section 5. A slightly modified budget for next year is given for the original amount of $ 75,000.

3.-DEVELOPMENTS RELATED TO THE LASER INSTRUMENTED GRADIOMETER CONCEPT

In this section we review the present concept of the laser instrumented gradiometer (section 3.1 and 3.2) and discuss the requirements on the laser instrumentation (sections 3.3 to 3.5). We also discuss in some detail the concepts and advantages of the "zero-derivative force" and light beam "side-injection" (sections 3.6 and 3.7).

3.1.-CONCEPT OF LASER INSTRUMENTED GRADIOMETER

The present conceptual status of the laser instrumented gradiometer is shown schematically in fig. 1. It consists of a laser driven double-delay line sensing the differential distance between two pairs of freely-falling proof masses. It provides a measurement of the difference in the gravity gradient along the directions of the two delay-line cavities. Two other versions of the gradiometer which are closely related to this one are also under study: in one of them, one cavity is a temperature controlled reference cavity providing a reference length. In this case, a direct measurement of the gravity gradient along the axis of the other cavity is obtained. In the other version, the frequency of the laser is controlled by the observation of saturation peaks in an external absorption cell containing an appropriate gas. Then, a single cavity is adequate. The laser beam interferes with itself and a gravity gradient along the axis of the single cavity is obtained.

Low frequency drift of the proof masses is prevented by electromagnetic forces. Along the direction of the delay-line cavities, these forces should operate in the frequency band dc to ≈ 0.01 Hz. The frequency band of greatest interest for the signal is ≈ 0.1 Hz to ≈ 10 Hz. The signal bandwidth could extend to kHz frequencies where the gradiometer would become (in its present design) a low sensitivity gravitational radiation detector.

3.2.-SENSITIVITY GOALS

The design goal is for the noise power density in the gradient measurement to be at the level of $\Gamma(\omega) = 10^{-4} E/\sqrt{Hz}$. The corresponding proof-mass displacement is $x(\omega) \cong 5 \times 10^{-13} (1/\omega)$ $m/\sqrt{Hz}$ where the average distance (base-line) between two proof masses is assumed to be 1/2 metre and where ω is the signal angular frequency. The force associated with such a gravity gradient is $f(\omega) = M\,\Gamma(\omega)/4 = 10^{-14}$ $N/\sqrt{Hz}$ for M=0.5 kg.

In sections 3.3 to 3.5, quantum and classical noise contributions will be evaluated. Where needed, it will be assumed that the laser wave-length is 632 nm and that the number of round trips in the cavities is 50 (100 reflections).

3.3.-QUANTUM NOISE AND LASER POWER REQUIREMENT

The shot noise associated with fluctuations in the arrival rate of individual photons at the photo-detector is a fundamental source of noise in interferometer instrumentation. In the best case, this shot noise exhibits a Poisson distribution. This leads to an error in the fringe phase measurement and to a corresponding error in the position measurement which, for the averaging time τ and for a double interferometer measurement, is given by:

$$\delta x_{sn}(\omega) = \frac{1}{8\pi\, n_t} \sqrt{\frac{2\, hc\lambda}{\eta P}} \quad , \qquad (1)$$

where n_t is the number of light-round-trips in each cavity, h is Plank's constant, c is the speed of light, λ is the light wave length, η is the photo-detector quantum efficiency and P is the laser power at the photo-detector.

If the laser beam is bounced off mirrors attached to the proof masses 100 times, the laser power required to overcome the noise associated with the Poisson shot noise is 100 microwatts. This is easily achieved with current commercial lasers.

In addition to shot noise, the laser interferometric measurement also exhibits a quantum back-action effect. The fluctuations in the arrival rate of photons at the surface of the proof-mass mirrors result in fluctuations in the radiation pressure and in the appearance of a radiation noise force which drive the proof-masses and introduce noise in the gradiometer. For a laser which displays Poisson noise, the spectral density of that force is:

$$f^2_{qp}(\omega) = 8\ n_t^{\ 2}\ Ph/\lambda c \quad . \tag{2}$$

This quantum back action is negligible in our case. With 100 reflections and 100 microwatts laser power, $f_{qp}(\omega)$ is of the order of $10^{-18}N/\sqrt{Hz}$, and 4 orders below the signal.

The considerations in this section indicate that the quantum noise associated with a laser power level of 100μw would permit operation at the sensitivity goal of $\Gamma(\omega) = 10^{-4}E/\sqrt{Hz}$.

3.4.-QUANTUM LIMIT.

The two expressions given in the preceding sections can be used to derive the quantum uncertainty relationship associated with laser measurements. Eqs. (1) and (2) can be expressed in the following way:

$$\delta x_{sn}(\omega)\quad f_{qp}(\omega) = \frac{\hbar}{\sqrt{\eta}} \quad . \tag{3}$$

$f_{qp}(\omega)$ results in momentum inacuracies $\delta p_{qp}(\omega)$ of an equal value. If double-sided quantities are used and represented by Δ, then:

$$\Delta x_{sn}(\omega)\quad \Delta p_{qp}(\omega) = \frac{\hbar}{2\ \sqrt{\eta}} \quad , \tag{4}$$

which, in the limiting case $\eta = 1$ reduces to the known uncertainty relationship.

3.5.-CLASSICAL NOISE AND INTERFEROMETER REQUIREMENTS

3.5.1.-POWER STABILITY REQUIREMENT

Fluctuations in the laser power produce a change in the average pressure on the proof masses. With 100 reflections and 100 microwatts average power, the average pressure is of the order 10^{-10}N. Thus, the spectral density of the fractional power fluctuations should be less than $10^{-4}/\sqrt{Hz}$. Control of laser power to $10^{-5}/\sqrt{Hz}$ has been achieved by Berstein at Maryland. Thus, adequate control of laser output power can be achieved.

3.5.2.-FREQUENCY STABILITY REQUIREMENT

Here, we consider two possible instrumental approaches: one and two-arm interferometry.

One-arm interferometry:

In a one-arm interferometer, any change in the frequency is indistinguishable from a change in the measured distance between the proof masses. In such a case, the frequency stability requirement is $(60/\omega)$ Hz/$\sqrt{Hz}$. The highest stability commercially available is 5000 Hz/$\sqrt{Hz}$. With such lasers, two-arm interferometry would be needed. Laboratory lasers with stability of 100Hz/$\sqrt{Hz}$ have been built and extension of their stability to millihertz levels is anticipated in the future. Thus, one-arm interferometry appears as a potentially practical approach to space gradiometry.

Two-arm interferometry:

If the two arms of an interferometer have the same length, frequency instabilities in the laser light can be neglected. In practice, some difference in length ΔL will exist. For $\Delta L/L = 10^{-3}$ and $\delta\nu$ = 5000Hz/$\sqrt{Hz}$, the error in the proof-mass position will be $\cong 4\times10^{-15}$m/$\sqrt{Hz}$ and approximately two orders below the signal. Thus, the required frequency stability required for two-arm gradient interferometry can already be found in some commercial lasers.

3.6.-SIDE INJECTION FOR COMMON MODE BALANCING

As shown in fig. 1, the laser light is injected into the delay line from a point located between the two mirrors associated with that line. For that particular configuration, there is no change in the delay-line optical length if the two proof masses associated with it are subjected to the same acceleration along the delay-line axis. Thus, side injection confers common mode rejection to the laser instrumented gradiometer. This common mode rejection is performed before any signal transformation or processing. This is an extremely important feature which considerably reduces the demands on the slew rate and linearity of the processing electronics.

3.7.-ZERO DERIVATIVE LOW FREQUENCY RESTORING FORCE FOR THE REDUCTION OF TEMPERATURE CONTROL REQUIREMENTS.

Restoring forces acting in the frequency range dc to $\approx$ 0.01 Hz and acting on each proof mass are needed to prevent drift of the proof masses with respect to the satellite and to compensate for the quasi-dc component of the earth field gradient. The force discussed in this section is the one acting on each proof mass along the axis of the delay-line cavity or along the axis of the measurement. The restoring forces needed in directions normal to that axis are referred to as lateral restoring forces or suspensions and are discussed briefly in section 5.2.3.

Mechanical or electromagnetic restoring forces are applied to a proof masses from a reference point or point of support attached to a base which experiences temperature fluctuations. Resulting changes in the dimensions of the base can produce changes and corresponding errors in the restoring force applied to the proof mass. Such errors will not arise, however, if the derivative of that force with respect to the relative position of the proof mass and the base is zero (to first order). We have initiated a study of ways to achieve that property. Voice-coil type magnetic restoring forces can be made to satisfy such a requirement. We are considering magnetic systems which would provide zero-derivative restoring force and would be sensitive to high order derivatives of the magnetic field. This latter property would reduce the gradiometer sensitivity to locally generated and residual Earth magnetic field in a satellite environment. Such zero-derivative suspensions sensitive to high order derivatives of the magnetic field are very desirable since they would dramatically reduce the related temperature control and residual magnetic field requirements.

4.-HARDWARE DEVELOPMENTS

4.1.-SILICON SUSPENSION TESTS

Early in this first year, Q values for aluminum and silicon suspensions have been measured. The purpose was to estimate the noise introduced into a gradiometer if such suspensions were used to provide the required restoring forces. In view of our progress in the understanding of zero-derivative restoring forces, we are now considering electromagnetic restoring forces which can be more easily designed to exhibit that property. These restoring forces can easily be made to operate at frequencies significantly below the signal frequencies. No significant difficulties are expected in maintaining these noise contributions in the signal frequency band at a satisfactory level since the ratio of the maximum gradient ($\approx$ 2000 E) to the desired noise level (10^{-4} E) is less than the ratio between a voltage and the minimum noise level that voltage will exhibit ($\approx 10^{8}$).

4.2.-DESIGN OF THE FIRST INTERFEROMETER

It is first planned to investigate the low frequency noise in a interferometer where the proof masses are fixed. This will permit a familiarization with multiple-reflection delay-line techniques. The initial setup will use a small number of passes in the delay line, approximately ten, over a distance d of about 50 cm between concave mirrors.

One reason for keeping the number of passes down is to allow the use of smaller mirrors. The spot diameters should not overlap. With approximately 3 mm spot diameter on a usable mirror radius of 19 mm (.75"), there is room on a 5 cm diameter mirror for at most 39 spots. A number smaller than this allows for less precise alignment. Smaller mirrors are desirable because of lower cost and wider availability. After layout optimization with the prototype, larger mirrors can be carefully selected and ordered.

The radius of curvature of the mirrors has been determined by a number of considerations. For a stable delay line, the maximum separation is limited to 2 times the mirror radius r. So for a separation d of 50 cm, r must be greater than 25 cm. Outside of that restriction, the separation d and mirror radius r are related by the type of spot pattern. The relationship between the number of passes ν in the delay line and the mirror parameters d and r is given by (Herriot, Kogelnik, and Kompfer, Applied Optics 3, 523 (1964))

$$2\nu\theta = 2\mu\pi \qquad (5)$$

$$\cos\theta = 1 - d/r \qquad (6)$$

Here ν is the number of round trips in the delay line and μ is any integer. 2θ is the angle between spots on either mirror. This condition is for a circular re-entrant pattern. To avoid an early exit, ν and μ should have no common divisors.

The other constraint on the choice of mirror radius is availability. After some search, it was found that 100 cm radius mirrors of high quality are widely available, from Newport, CVI Laser, and other sources. With the choice of mirror radius, the integers ν=11 and μ=4 were chosen to allow 11 round trips in the delay line with a mirror separation of 58 cm.

The MIT group uses an EG&G SGD-444 photodiode to detect their interferometer output. The active area of this device is 100 mm^2, which is sufficient to contain the expected spot diameter of 3 mm. The EG&G FFD-200 device has better performance characteristics but only 20 mm^2 active area. It may be possible to change to the FFD device if the beam diameter and divergence are found to be small enough.

The EG&G SGD-444 photodiode has been selected for our initial study. It has a responsivity R of 0.35A/W at 632 nm for a quantum efficiency $hcR/(q\lambda)$ of 0.69. The capacitance of the SGD-444 is 46 pF when biased at -200 V and the series resistance is 50 Ω. The FFD-200 will also be considered later because it has smaller values of C and R which are better for matching to a low-noise amplifier.

The shot-noise level for the laser at the output of the photodiode depends on the contrast of the interferometer as well as the laser power and the modulation amplitude. Using an average power of 0.25 mW, contrast 0.9 and modulation of 1 radian, the dc current out of the photodiode contributing to the white noise is 50 μA, with a corresponding noise current of 4 pA/$\sqrt{Hz}$. Current amplifiers from Analog Modules with current noise level lower than this are available but will not work with the high junction capacitance of 46 pF. The load resistor used by MIT of 50 Ω has a voltage noise of 0.9 nV/$\sqrt{Hz}$. The noise current would produce a voltage of 0.2 nV/$\sqrt{Hz}$. A better match can be made in our case by using a larger load resistor, provided the amplifier dynamic range is adequate. The larger laser power used at MIT makes the 50 Ω resistor appropriate for them.

The Analog Modules model 322-8-200 amplifier can be used with a 400 Ω load resistor. With that value, the laser shot noise level is 1.6 nV/$\sqrt{Hz}$, the resistor noise is 2.5 nV/$\sqrt{Hz}$, and the amplifier noise is 0.4 nV/$\sqrt{Hz}$. This is a reasonable match for the initial tests. For better sensitivity, a larger load resistance and a custom amplifier such as the one used by the laser interferometer group in Munich will be used (we have obtained a schematic of their design).

4.3.-PROGRESS IN THE ASSEMBLY OF THE FIRST INTERFEROMETER

Mechanical and optical components for the first interferometer have been selected. All have been ordered including an 6' x 4' optical table. Some components have been delivered. We are in the process of testing the components we have received. Design of a vacuum chamber for the temperature control and operation in vacuum of the interferometer is also in progress.

5.-PLAN FOR NEXT YEAR

5.1.-LASER INSTRUMENTATION

Early in the year, a table setup consisting of a two-arm interferometer as shown on fig. 1 will be completed. The (mirror) proof masses will be fixed. This table set up is for initial familiarization with the system operation and layout optimization.

Next, the two-arm interferometer will be reproduced on a superinvar support. The proof masses will again be maintained at fixed positions. Temperature control will be used and the interferometer will be operated in vacuum. This will permit a study of the noise components of a laser gradiometer in the low-frequency region of interest: ≈ 0.1 Hz to ≈ 10 Hz.

5.2.-SUSPENSION INVESTIGATIONS

Suspensions for three different purposes need to be developed. That problem will also be addressed in the coming year. We plan to study schemes to implement such suspensions and fabricate prototypes if sufficient design progress is made and manpower permits.

5.2.1.-MAGNETIC SUSPENSIONS FOR EARTH BOUND TESTS

To perform tests of the interferometer as a gradiometer, it will be necessary to provide a vertical suspension for the test masses. A magnetic suspension is presently considered for that purpose. It would consist of permanent magnets attached to the interferometer support and to the test masses with fields of opposite direction facing each other. A stable configuration will be selected and noise tests planned.

5.2.2.-VOICE-COIL FORCE AS ZERO DERIVATIVE FORCE

A voice-coil type force can provide "zero-derivative" positioning force. Such force will be considered for maintaining the test masses in their proper position in the direction of the laser light propagation (or along the gradiometer axis).

5.2.3.-LATERAL SUSPENSIONS WITH HIGH Tc SUPERCONDUCTORS

Suspension are needed to prevent excessive displacement of the test masses in a direction normal to the light propagation (gradiometer axis). Pressure forces as provided by a superconducting current facing a superconducting surface will be considered for this task. Since very small forces are needed here, it is expected that this can be accomplished with the new high-temperature superconductors.

6.-RELATED PUBLICATIONS / VISIT TO LABORATORIES / CONFERENCES

We attended the 1986 Gravity Gradiometry Conference, Colorado Springs, Colorado and presented a talk on a laser instrumented gradiometer.

We also attended the 1987 Gravity Gradiometry Conference, and plan to attend the 1988.

We attended and presented a paper at the International Laser Science Conference, Atlantic City, Nov. 1-4 1987.

We visited ONERA in France where the space gradiometer GRADIO is being constructed ($10^{-2}E/\sqrt{Hz}$) and also two laboratories located at Villetaneuse and Saclay where very high stability lasers are being developed for high precision frequency and position measurements. Many very instructive internal reports were brought back.

We visited Professor R. Weiss and his colleagues at MIT and brought back voluminous documentation on laser instrumentation produced by them over the last 15 years.

7.-SUPPORT

Dr. William Folkner, a brillant Post Doctoral Associate with previous experience at Los Alamos has completed his Ph.D. and will spend a significant part of his time on this project.

The University of Maryland has provided laboratory space for our development of the laser instrumented gradiometer.

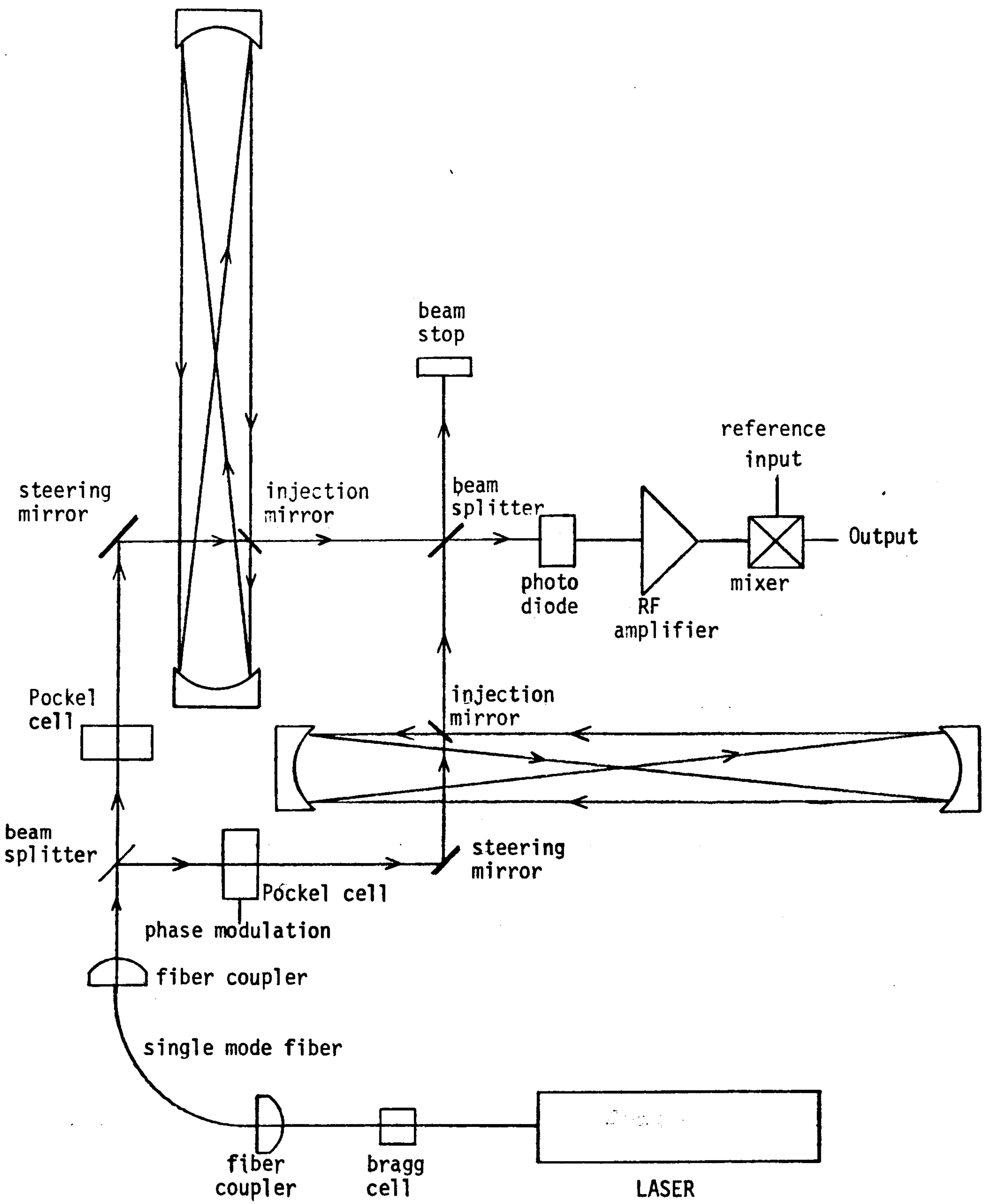
The quantum optics group at the University of Maryland includes Professors D. Currie who is developing long base line optical interferometry. We already have had numerous discussions with him and some of his postdoctorate assistants.

The research effort described here greatly benefits from discussions with John Giganti, a brilliant electrical engineer. Mr. Giganti has been involved in the Apollo 12 experiment and is currently involved in two laser projects with two colleagues in the department. His time is paid for by the department.

A proposal has been submitted to the National Science Foundation for laser instrumentation of wide-band multi-mode gravitational radiation detector of our invention. Such a program would offer significant cross-fertilization with the laser instrumented gradiometer effort and would accelerate progress accordingly.

FIGURE CAPTION

Fig. 1. Double delay line interferometer with side injection scheme. The laser output passes through a Bragg cell to provide isolation for the laser from reflections from the interferometer input which would worsen the frequency stability. The Bragg cell also provides a means of controlling the laser amplitude. The beam then is injected into a single mode fiber, which removes any side bands and feeds the light into the vacuum chamber. After the initial beam splitter, the beam passes through the Pockel cells. One Pockel cell is used to phase modulate the laser beam for the AC readout scheme in a frequency regime where the laser noise is shot limited. The other Pockel cell is used to keep the optical paths of the two arms balanced. The steering mirrors reflect the beam to the double-sided injection mirrors to the delay lines. The outputs from the multiple-pass delay lines reflect off the back side of the injection mirrors to the second beam splitter/combiner. One beam then goes to the photodiode to provide the output for the interferometer. The photodiode output is amplified and mixed with the phase modulation reference signal to convert the interferometer output to DC. The other beam from the second beam splitter/combiner is trapped, but can be used in future designs as an amplitude stabilizing reference.


beam
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mirror
beam
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steering
mirror
Pockel cell
phase modulation
fiber coupler
single mode fiber
fiber
coupler
bragg
cell
LASER

Fig. 1

"Monocrystalline Silicon Gradiometer
For Gravity Experiments in Space"

NASA Grant NAGN-1003

January 1, 1988 - December 31, 1988

		Research		Equipment Construction	Total
Prof. J.-P. Richard Principal Investigator	1 mo	4,851			4,851
R. Folkner Research Associate	2 mo	4,937	3 mo	7,406	12,343
C. Connor Secretary	1.5 mo	2,353			2,353
P. Pei Account Clerk	0.5 mo	784			784
Total Salaries		12,925		7,406	20,331
Benefits		3,198		1,300	4,498
Total Salaries & Benefits		16,123		8,706	24,829
Domestic Travel		1,500			1,500
Foreign Travel		1,000			1,000
Materials & Supplies		500			500
Publication		1,000			1,000
Mechanical Shop		1,500			1,500
Other		650			650
Total Other Direct Costs		6,150		0	6,150
TOTAL DIRECT COSTS		22,273		8,706	30,979
Indirect Costs 40.5% On Campus		9,021		0	9,021
Equipment Components		35,000			35,000
Total Budget		66,294		8,706	75,000

EQUIPMENT BUDGET FOR SECOND YEAR OF NASA GRADIOMETER GRANT

Super-invar breadboard, Newport XI-22		3000
Fixed delay lines		
Mirrors, CVI SM2-1	1500	
Super invar mirror mounts	1250	
Custom grind mirrors	500	
Super invar rods, 6 ea.	250	
Custom grind rods	500	
Super invar optics mounts	1000	
		5000
Vacuum chamber		
Bottom, top plates	500	
Sides	1500	
Electrical, optic feedthru	500	
		2500
Oil-free pumping system		
Pump, Varian 941-6501	525	
Dewar, Varian 944-0010	125	
Heater, Varian 944-0044	250	
Thermocouple, Varian 801	200	
Valves, Key BA60, 3 ea	200	
Assembly	700	
		2000
Thermal control system		
Super insulation material	300	
T sensors, Omega PR-11,4 ea	300	
T control, Omega 4201, 4 ea	1200	
Heaters, Cole-Parmer T 3125	200	
		2000
Waveform analyzer, Data Precision 6100		13000
Bragg modulator, Crystal Tech. 3080		1000
Plotter, HP 7470		1000
RF amp for Pockel cells, AR 50A15		2500
Zenith model 248 microcomputer		1800
Feedback amplifier, custom made		1200
TOTAL		35000