Extension of Gravity-Wave Interferometer Operation to Low Frequencies, and to other fields

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Abstract.

Experiments relating to concepts for extending interferometer operation, particularly at low frequencies, are discussed. This includes work with suspensions connected by a suspension-point interferometer. A new concept for achieving similar frequency extension without requiring an additional interferometer between suspensions is outlined, as well as a technique for improving positioning of laser beams relative to centers of gravity of test masses in gravity wave interferometers and other instruments.

1. Introduction.

For some time now we have been studying and testing a variety of potential techniques for extending downwards the operational frequency of long-baseline gravity-wave interferometers. Here we will report some recent work relating to the use of what has been called a "suspension-point interferometer", a technique for improving seismic isolation at frequencies extending down to well below 1 milliherz.

The basic concept involves monitoring by auxiliary interferometers any changes in separation between the upper attachment points of wire or fiber suspensions supporting the test masses at the ends of each main interferometer arm. In a multiple-pendulum suspension the additional interferometer may be formed between mirror coatings on the penultimate masses of each interferometer chain, as illustrated schematically in Fig. 1 for a single interferometer arm. In one mode of operation feedback forces may be applied to maintain relatively constant the lengths of the upper and lower interferometer beams. Residual motions from the preceding isolation system are then forced to become equal at both ends of each beam, in the beam direction, and thus may be made to cancel in the main interferometer output, at least to first order.

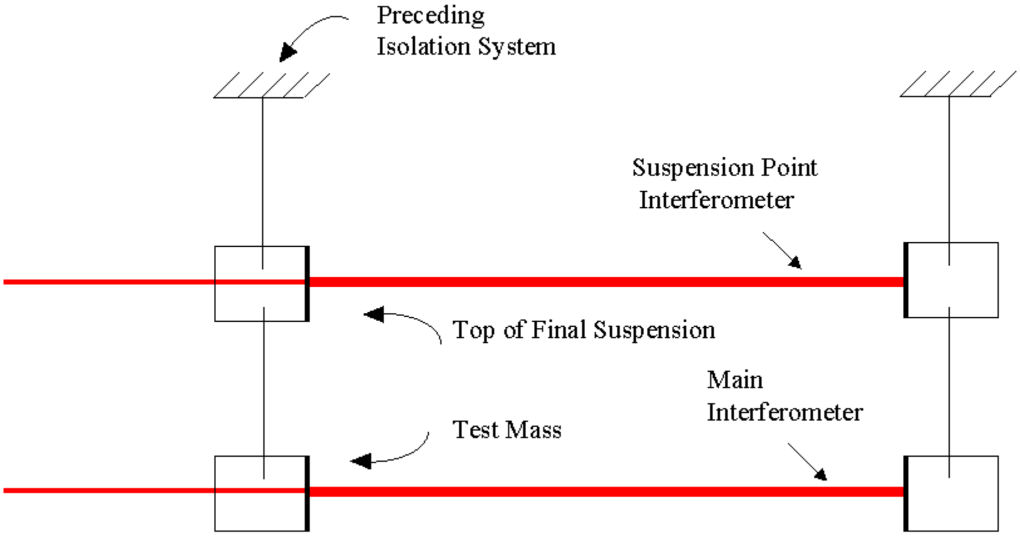

Figure 1. Schematic arrangement for one arm of a "suspension-point interferometer system" for the case of a multiple-pendulum suspension.

This idea [1,2] is an old one and was proposed by one of us in the late 1970's. Our more recent interest in it came from the realization that as it should allow practical operation at frequencies below that achievable with current passive or active filter-type isolation systems, it would not only give a reserve for gravity-wave observations but would also make possible ultra-sensitive measurements [3] of changing gravity gradients which could be of importance in themselves. For example T.H. Heaton has pointed out [4] that ground motions at a distant earthquake could give prompt gravity gradient changes in the frequency range 0.1 to 1 Hz, a convenient range for initial tests. Gravity gradients at sub-milliherz frequencies which might arise from oscillations of the solid core of the earth have also been considered [5].

To gain some experience of the practical problems in interferometer measurements at low frequencies we have been making preliminary tests in one arm of a 40 m interferometer system. We began with a relatively simple one-bounce interferometer.

2. Tests with a one-bounce interferometer system.

A simplified schematic diagram of our first test system is shown in Fig. 2. Here we used a pair of unequal-arm interferometers, one for the lower beam and the other for the upper beam. Each had one 40 m arm and a very short second arm located inside each input mass, and both were illuminated by light from a HeNe laser stabilized to a neon line, with output frequency monitored by a stable optical cavity. In all these experiments the interferometers were operated in feedback mode, with high open-loop gain in the length servo-systems, and the outputs recorded were proportional to the feedback forces applied to the test masses. Corner reflectors were used to reduce requirements for active orientation control of the masses. However our early experiments showed a near-periodic signal with periodicity around 24 hours, which we tracked down to a day-night periodicity in the laboratory temperature. This caused periodic feedback forces to be applied to the upper masses. Small unbalance in these forces caused some rotation of the masses, which with imperfections in the corner reflectors led to the observed signals. These effects were eventually minimized by introducing a thermal control system to reduce changes in distance between the main upper suspension points, and optical lever control of mass orientation. At this stage use of optical cavity sensing became useful and practicable, and experiments switched to a Fabry-Perot interferometer system.

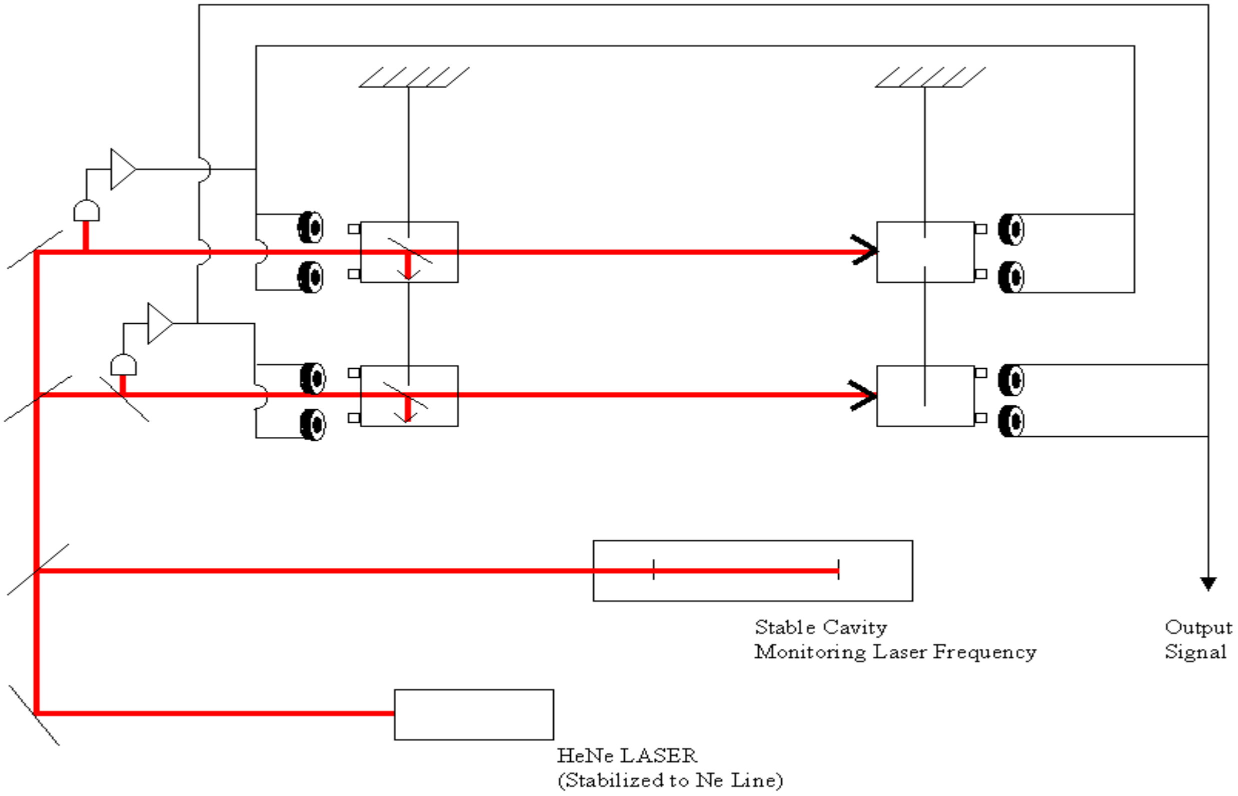

Figure 2. Simplified schematic diagram of the one-bounce single arm test system used in preliminary experiments.

3. An optical-cavity suspension point interferometer.

A simplified schematic diagram of the cavity interferometer, still under development, is given in Fig. 3. In this case a Nd.YAG laser was used, with a resonant frequency doubler giving green light compatible with the coatings on some existing fused-silica test masses, and frequency stabilization to a stable reference cavity. Single-loop wire suspensions are used for both upper and lower masses, with small bridge stand-offs on the upper masses to keep the wires separate.

At present construction and development of this test system is in progress. The experience gained from the previous interferometer and from the construction of this one has already stimulated some further ideas. We outline two of these now.

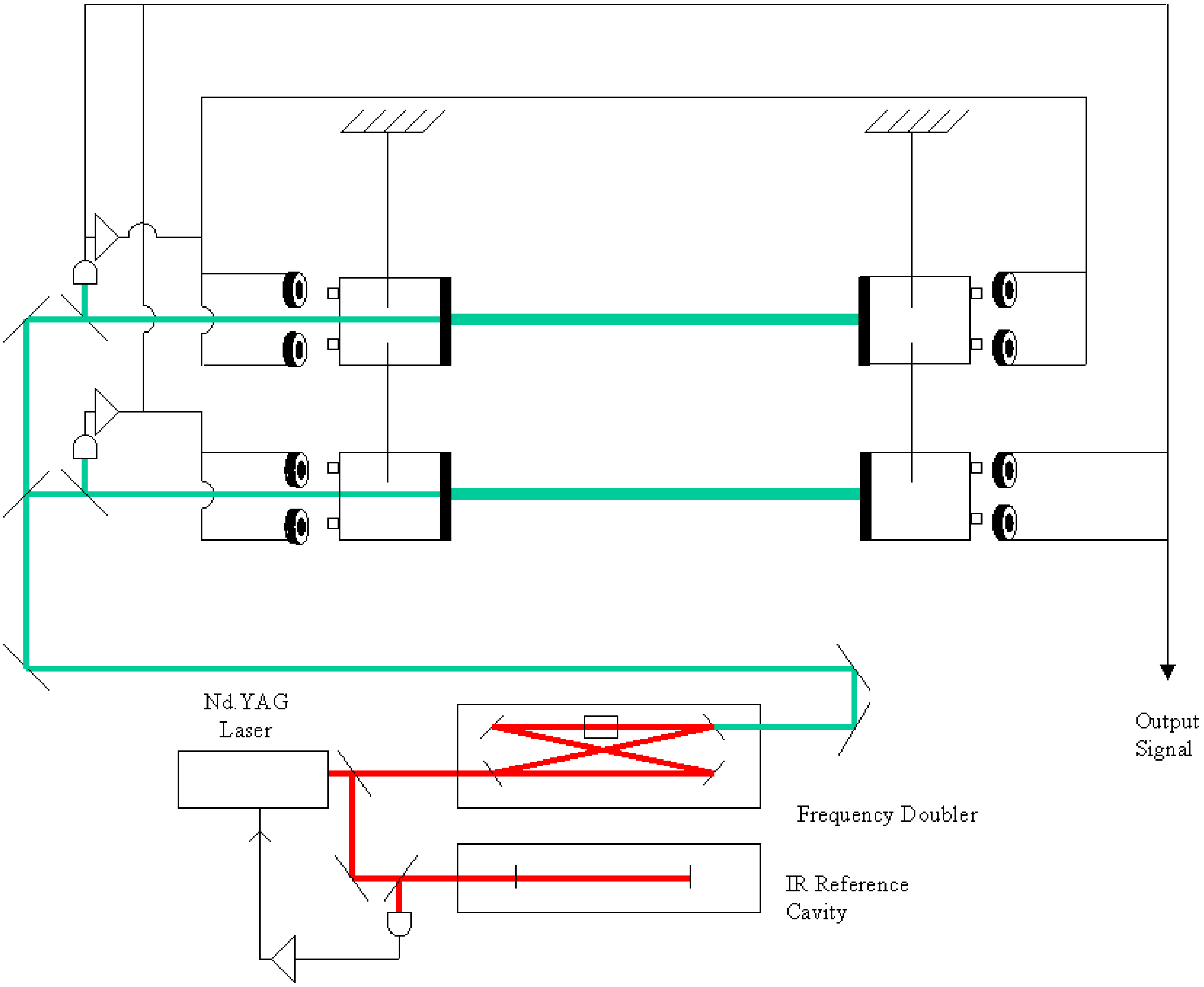

Figure 3. Schematic diagram, highly simplified, indicating the cavity system under construction.

One of the mass assemblies is illustrated in Fig. 4, and an overall view of the system is given in Fig. 5.

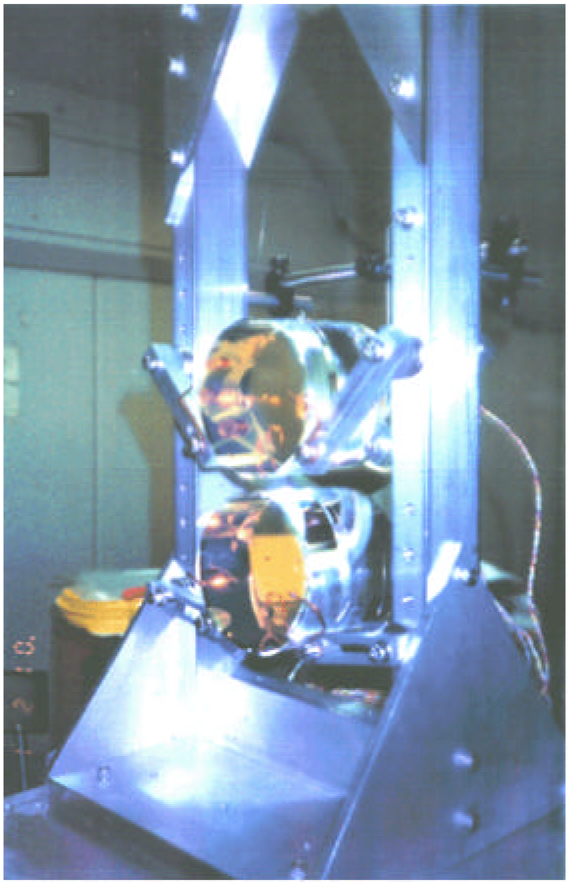

Figure 4. One test-mass suspension assembly for the cavity interferometer, removed from the vacuum system.

Figure 5. The test system used: the 40-m beam-tube at the right-hand side of the photograph houses the interferometer experiments outlined here.

4. A new low-frequency interferometer design.

The basic type of suspension-point interferometer arrangement outlined above looks likely to be an effective system. However, the second long interferometer beam may be a practical inconvenience, particularly if the technique were to be intended as an addition to an existing large interferometer system. We outline now a possible way of achieving some of the main characteristics of this system without introducing additional beams along the whole lengths of the interferometer arms. It was pointed out by D. DeBra [6] that one might consider the possibility of obtaining a measure of the distance between the suspension-points by using small local interferometers to monitor relative motions between the upper and lower masses at each end of the arms, and combining the data from these short interferometers with that from the main beam. There is, however, a serious difficulty: the local measurements required are sensitive to differential changes in tilt of the test masses or of other local reference directions. We propose here to avoid this by using the direction of the main laser beam as a common reference direction for the measurements at both ends of each arm. This may be implemented by using the "wavefront-sensing" technique [1, 7] devised by one of us in 1984, to hold the test mass orientations locked to the beam direction. A possible arrangement is indicated schematically in Fig. 6. Here each local interferometer uses a short cavity formed between a small mirror, attached by a rod to the upper mass, and an area of the coating of the lower mass near it’s edge. The geometry of the wire suspension between the upper and lower masses is arranged to maintain the axes of masses parallel to one another, by using two or more wires. The particular arrangement shown here was chosen largely for clarity of explanation. The general technique and its variants may provide a very practical way of improving a conventional suspension system to give milliherz operation and significantly extend its usefulness.

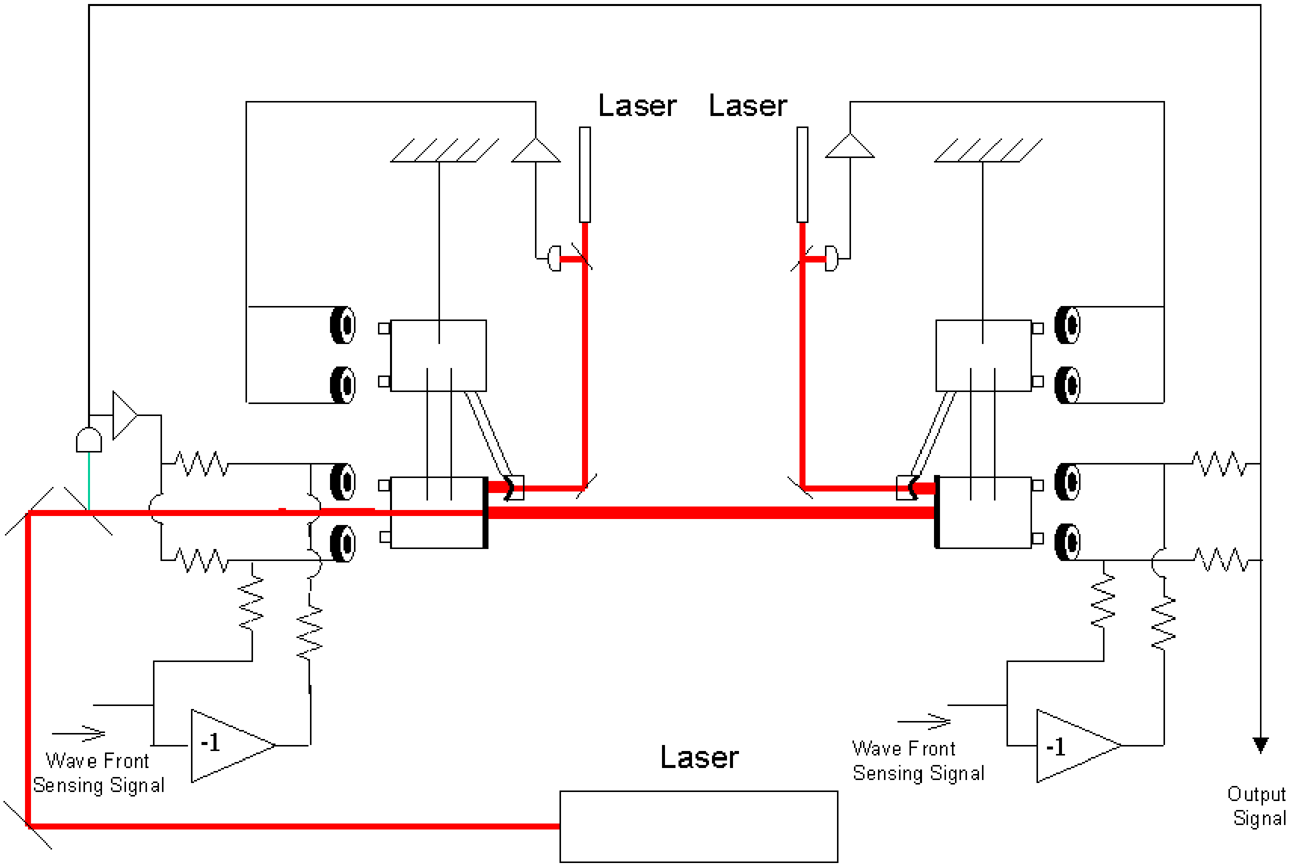

Figure 6. Diagram to illustrate the concept for the single-beam low frequency interferometer arrangement outlined here.

5. A technique for automatic beam centering.

Our experience with these low frequency interferometers is already showing that several of the noise and technical problems encountered are more troublesome than those which had to be overcome at the usual gravity-wave frequencies. It may be difficult to achieve adequate control of test mass orientation, since the control forces required may have noise at frequencies which overlap signals of interest. This has led us to consider the possibility of an automatic technique for precisely controlling the laser spot position relative to the center of gravity of each test mass, as a means of reducing sensitivity to residual orientation errors. We propose using internal vibrations of each test mass in modes which give nodal lines crossing the center of the mirror coating, such as a first-order bar mode, to modulate tilt of the front surface. By observing the phase and amplitude of any resulting interferometer length signal appearing at the frequencies of relevant modes, the distance of the beam spot from the nodal lines may be determined. It may be possible to use natural thermal vibrations if a wavefront-sensing system of sufficient sensitivity to determine the phase of the vibrations is used, or alternatively the modes of interest may be driven at larger amplitude with known phase by an external source. If there is a small asymmetry in the test mass, as might arise from a wedge angle between the faces often used to avoid back reflection effects, orthogonal modes would have slightly different frequencies. Thus, the components of the correction signal in two directions required to control a servo-system to bring the beam to the center of the mirror face can be determined. To enable the errors from each test mass in an interferometer to be identified it may be arranged that the masses have slightly different resonance frequencies.

A useful and important aspect of this suggested technique [8] is that it may directly relate spot position to the centers of gravity of the masses.

6. Conclusion.

It is expected that techniques outlined will be useful in extending gravity-wave interferometer operation to much lower frequencies both for gravity-wave research and for gravity gradient measurement in other fields.

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References and Notes.

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[6] We are happy to acknowledge this stimulating suggestion made by D. DeBra at the 2001 Aspen Winter Conference on Gravitational Waves, February 4-10. 2001, after a presentation of some of the work reported here.

[7] Morrison, E., Meers, B.J., Robertson, D.I., Ward, H., Automatic alignment of optical interferometers *Applied Optics*, 33, p.5037-5040 or 5041-5049 (1994)

[8] After the presentation of this paper at the Amaldi Conference it was learned that similar ideas have also been considered in one or more other groups.

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