A STUDY OF A LONG BASELINE
GRAVITATIONAL WAVE ANTENNA SYSTEM

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Introduction

This document is the result of a study of the sensitivity, design and costs for a gravitational wave detection system based on interferometric long baseline antennas. The study was initiated by the MIT Gravitational Research Group who engaged the engineering firms of Arthur D. Little of Cambridge and Stone and Webster of Boston. Arthur D. Little studied the vacuum system design and costs while Stone and Webster made an evaluation of sites and studied various construction concepts and their costs. The spirit of the costing exercise was to fix on a design but at the same time to establish the cost scaling laws applicable to other designs.

In later phases of the study, the advice and criticism of the Cal Tech Gravitational Research Group were sought. Parts of this study have benefited from this interaction, however the tyranny of the schedule to complete this document have left substantial parts of it without their constructive review.

The principal conclusion of this study is that it is timely and feasible to construct a gravitational wave detection system based on at least two long baseline interferometric antennas. The development could open a new field of astrophysics--gravitational astronomy--with its own unique sources and insights into the universe and gravitation. The technical ability exists now to extend the search for gravitational radiation into new frequency bands and to gain a million fold increase in energy sensitivity over present detection systems.

Furthermore, there is substantial margin for further improvement in the sensitivity with technical advances as the fundamental limits for these systems are still many orders of magnitude below the projected sensitivities.

The positive conclusion of this study may have been anticipated. It could have been otherwise: the basic concept could have been flawed, the technology could have been inadequate, the costs could have been beyond reasons. None of these appears to be the case.

HISTORY AND OVERVIEW

The concept that gravitation along with all other interactions in nature propagates with finite speed originates with Einstein and special relativity in 1905. The formulation of relativistic theories of gravitation began after the discovery of special relativity and continues to this day. A central feature of all of these theories is gravitational radiation.

The choice made in this report and in most but not all prior attempts at detection of gravitational radiation has been to focus on the tensor waves predicted by Einstein in 1918 as one of the theoretical results of general relativity. These waves are expected to be transverse with two polarization states and propagate at the velocity of light. General relativity, by virtue of its simplicity and elegance, has been the favored relativistic gravitational theory since its formulation in 1916. However, the experimental basis for its acceptance has not been strong. Experiments and observations performed terrestrially and in the solar system during the past twenty years have established that in the low velocity, weak field limit general relativity is a proper description of nature. The discovery of PSR 1913+16, a binary system consisting of a pulsar orbiting a neutron star, has been an important element in improving the experimental basis for general relativity. This system is found to obey all the dynamical predictions of general relativity at weak fields and in addition appears to be decreasing its orbital period--

shedding energy-- at just the rate required by gravitational radiation damping as expected by general relativity. This is the first experimental evidence for gravitational radiation and a strong indicator that the Einstein tensor waves are the right ones to look for.

The actual detection and the experimental verification of the wave properties has not been accomplished. This alone is sufficient motivation to carry out the search. One might imagine that an experimental program similar to the Hertzian experiments with electromagnetic waves, where the source and receiver are under the experimenter's control, would be the appropriate method for such a study. Unfortunately it is just here that the extreme weakness of the gravitational interaction strikes hardest. The gravitational strain amplitudes, the measurable in the Einsteinian tensor waves, are always of the order

$$h \sim \left(\frac{GM}{Rc^2}\right) \frac{v^2}{c^2} \qquad (1)$$

where h is the strain, G the Newtonian gravitational constant, R is the distance to the radiating mass, M, which is moving with velocity, v. c is the velocity of light. In order to separate radiation from induction the observer must be in the wave zone at a distance of the order of the wavelength. For an oscillating system then, one would estimate the largest wave strains as

$$h \sim \frac{GM\omega^3 a^2}{c^5} \qquad (2)$$

where a is the oscillation amplitude of the radiating source at frequency ω. The reader can readily show that the G/c^5 factor is devastating when coupled to the masses, amplitudes and oscillation frequencies one might contemplate in a laboratory experiment.

Astrophysical phenomena involving the coherent motions of large masses at relativistic speeds are the sources most likely to give terrestrially measurable gravitational radiation strains and permit a study of the wave properties. It is, moreover, just these extreme phenomena that, if they can be made observable, will allow us to test relativistic gravitation in the strong field--high velocity limit. A view held by many is that this is the most important reason to engage the search for gravitational radiation. Implicit in this view is that signatures in the gravitational radiation may well be the most definitive means to establish the existence and study the interactions of black holes with their surroundings.

A review of the astrophysical sources that have been contemplated is given in this study and the interested reader is invited to turn to that section of the report. The theoretical predictions indicate that detection of gravitational waves by the proposed system is entirely plausible, but by no means guaranteed. In these introductory remarks it is worth highlighting a more speculative viewpoint which borders on a truism but is really at the heart of the matter. Should one succeed in observing gravitational radiation, the chances are excellent that specific and fundamental issues in gravitation will be settled. In addition the search itself, as it offers a new probe of the universe, may uncover totally unexpected phenomena. Both are exciting prospects and in our opinion make the search one of the most interesting scientific opportunities of this epoch.

None of the foregoing is intrinsically new except for the spectacular discovery of PSR 1913+16. Much of this was on the mind of Joseph Weber when he initiated the search for gravitational radiation using acoustic (bar) detectors[1] in the mid 1960s. Setting aside the controversy raised by the first experiments, it became clear, after a world wide effort, that nature was not as generous as might have been indicated in the early experiments. In a broad sense this realization was the beginning of the search in earnest; the arguments for carrying out the search remained persuasive, the sources were just not that strong nor, in hindsight, was it reasonable to expect that they could have been.

Impressive progress has been made in improving the sensitivity of acoustic antennas since the pioneering experiments. By lowering the operating temperature, choosing antenna materials with higher internal Q and the development of better position transducers coupled

[1] Acoustic detectors are usually longitudinal mechanical resonators coupled to motion transducers. The gravitational wave induces time dependent longitudinal stresses in the device which then responds as a harmonic oscillator to a time dependent external force.

to lower noise amplifiers, the strain sensitivity has been increased by a factor close to a thousand over the last decade. At the present (Fall 1983) one cannot make a sharp judgment that these improvements have not uncovered gravitational radiation sources. The best present system is operating at an rms strain sensitivity of approximately 10^{-18} near 1 KHz. Although conventional wisdom holds that it is unlikely to find sources at this level, the fact is that there has been no opportunity to run two such antennas in coincidence to find out for sure.

The hope is that acoustic detectors can be improved by approximately another two orders of magnitude in strain sensitivity before they may be limited by quantum fluctuations. Considerable theoretical effort has gone into analysing whether the quantum fluctuations do indeed impose a hard limit. The consensus is that in principle they do not but there is argument whether a practical scheme to circumvent the quantum fluctuations can be implemented and, if it can be, what improvements in sensitivity might result.

Our assessment is that acoustic bar antennas are the most sensitive devices with which to carry out the search at present and they will remain so for the next several years.

"Free" mass electromagnetically coupled antennas[2], the central

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[2] Electromagnetically coupled antennas measure the gravitational wave induced modulation of the travel time of light between masses that label points in space. The masses are free at frequencies above their suspension resonance. The concept is described in detail in the section of this report on the antenna response functions.

subject of this study, were first considered in the early 1970s both at MIT and the Hughes Research Laboratories independently. Although more complex and expensive than acoustic detectors, especially the low sensitivity room temperature bar detectors of the early experiments, it was recognized from the start that electromagnetically coupled antennas have several desirable properties when constructed on a large enough scale. The strain sensitivity is in principle better than that of an acoustic detector by the ratio of the velocity of light to the velocity of sound in solids. As there is no reliance on resonance to match the position transducer to the mechanical system, they are broad band and therefore useful in the search for all classes of gravitational radiation sources--periodic impulsive or stochastic. Furthermore if sources were ever to be uncovered with sufficient signal to noise, electromagnetically coupled antennas could follow the time dependent wave shapes of the gravitational wave metric perturbations with fidelity and be a powerful diagnostic tool in determining the radiative processes in the source. Finally, the practical realization of an antenna system designed to meet the sensitivities presumed to be astrophysically interesting, did not require more than the thoughtful application of even then current technology if the systems were made large enough. One might ask why no large project was started? The answer, simply stated, is that in the early 1970s the time wasn't right.

In the mid 1970s the Office of Space Science at NASA encouraged research in exploring the properties of electromagnetically coupled antennas deployed in space, using optical techniques to avoid the index fluctuations of the interplanetary plasma. It was realized that antennas in space would be able to measure gravitational radiation at long periods, minutes to hours. This region is inaccessible on the ground, but is interesting astrophysically; especially since this band includes the expected radiation from stellar binaries. The study of optical long baseline low frequency antennas is being carried on at JILA (University of Colorado) and at JPL and hopefully will be incorporated into the long range plans of the NASA Space Sciences Program.

By the mid 1970s the concept began to interest other research groups, especially in Europe, In 1974 the Gravitational Research Group at the Max Planck Institute in Munich, who had carried out the search for gravitational radiation with room temperature acoustic detectors, began developing an electromagnetically coupled antenna. The group then directed by Prof. H. Billing has constructed a 3 meter long prototype using multi pass delay line optics in a Michelson interferometer configuration similar in concept to the design at MIT. In the course of their experimental program they discovered and solved many of the technical difficulties in the practical implementation of the idea. To date, they have demonstrated the best performance of a prototype electromagnetically coupled antenna; their instrument is operating at an rms strain sensitivity of approximately 10^{-16} near 1 KHz. They are now developing a 30 meter version of this system and hope to go on to longer systems.

In the later 1970s the Gravitational Research Group at Glasgow University directed by Prof. R. Drever, who also had been involved in the search for gravitational radiation with acoustic antennas, began the development of electromagnetically coupled antennas.

The Glasgow group chose to use Fabry-Perot cavities as the antenna elements after preliminary experiments with multi-pass White cells mounted on a split bar acoustic detector. In the course of these early studies they discovered the problems associated with scattering of light which had not been adequately recognized earlier.

In the late 1970s Cal Tech made the decision to begin a program in experimental gravitation, the central focus of which has become the search for gravitational radiation using electromagnetically coupled antennas. Professors R. Drever and S. Whitcomb direct this effort. The Cal Tech prototype is a 40 meter Fabry-Perot system which has begun to function this year. The optical design is similar to the Glasgow instrument. The Cal Tech instrument is at present the largest prototype to come into operation.

We have learned recently that a group is being formed by A. Brillet at the Laboratoire de l'Horloge Atomique at Paris-Sud to develop a prototype electromagnetically coupled antenna, the state of this project is not known to us.

INTRODUCTION TO THE CONCEPT OF AN ELECTROMAGNETICALLY COUPLED ANTENNA

The basic concepts of an electromagnetically coupled antenna are presented in this section without mathematical encumbrance; these are left for more detailed presentations later in this document.

The fundamental idea is straightforward. The travel time of light between two objects in free fall,--travelling along geodesics of the four dimensional geometry of space and time--is modulated by a gravitational wave. The measurable quantities are the changes in the travel time. Except for geometric factors, the change in travel time is equal to the integral of h taken over the travel time. Since the gravitational wave strain amplitudes are expected to be small and there are as yet no time standards of the requisite stability, the difference in travel time of light propagating in two orthogonal directions is measured. This technique applies specifically to the polarization states of the Einstein tensor waves which have strains of opposite sign in orthogonal directions transverse to the direction of wave propagation. The relation between the measured time difference and h is primarily a function of the total time the light spends in the gravitational wave, this time is referred to as the storage time. And, except for subtleties, a single long light path is equivalent to the sum of many shorter ones. In simple geometries nothing is gained if the storage time is larger than 1/2 the gravitational wave period. As pointed out by Drever, this need not be a limit if the gravitational wave is periodic, for it is then possible to accumulate time differences for storage times larger than the gravitational wave period providing that one arranges the light beam to oscillate between the two orthogonal directions in synchronism with the gravitational wave period.

In practice, the time difference is not measured directly but rather the difference in phase of two light beams having traversed the orthogonal paths is measured interferometrically. The condition that the system be insensitive to clock instability is satisfied by making the optical paths in the two orthogonal directions equal.

The smallest gravitational wave strain measurable is determined by a host of perturbing effects which are broadly organized in two groups; those that limit the ability to measure the time (or phase) differences and those that compromise the assumption that the masses are truly free and unperturbed. A few of the effects are fundamental and others can be reduced by sound engineering practice. The influence of all effects that perturb the masses is reduced by increasing the physical length of the antenna.

A fundamental limit is imposed by quantum fluctuations which effect both the ability to measure the time differences and cause a perturbation on the masses. The limit can be analyzed heuristically much like the Heisenberg microscope but with many photons and macroscopic masses. It can also be viewed as an intrinsic quantum diffusion process. The limit is reduced by increasing the mass and the physical length of the antenna. As with the quantum limit for acoustic detectors, there is speculation that the quantum limit is not really fundamental but in the case of electromagnetically coupled antennas this argument is at present more academic both because the strain limits are so much lower than for acoustic detectors and that, in the first generation of large baseline electromagnetically coupled antennas, the other perturbing effects are expected to be larger than the quantum limit.

Time dependent gravitational gradients from distant sources, induction fields rather than radiation, are indistinguishable from gravitational waves in only one antenna and could be considered as imposing a fundamental limit. These are estimated to be very small in the frequency bands open for the search on the ground.

Less fundamental but at present more influential noise sources are thermal excitations of internal modes in the masses at high frequencies and low frequency motions in the suspension system that support the masses. These are reduced by using low loss (high Q) materials and could be further reduced by cryogenic operation in future refinements of long baseline antennas. Thermal noise does not play the same crucial role in determining the limit of electromagnetic antennas as in the acoustic types because one does not work on the resonances and the noise is reduced by increasing the antenna length.

Ground noise (seismicity) and acoustic vibrations communicate forces to the masses through the suspension. The noise becomes more influential at low frequencies because the excitation spectrum grows at low frequencies and vibration isolation systems become more difficult to implement at low frequencies. The reduction of this noise source requires more subtle engineering in electromagnetic than acoustic antennas primarily because of the intent to extend the search to lower frequencies. The influence of this noise term also reduces with antenna length.

A list of less significant perturbations on the masses includes the influence of time varying electric and magnetic fields, the momenta imparted to the masses by cosmic ray impacts, thermal gradient driven gas pressure forces, radiation pressure variations due to amplitude fluctuations of the light source, made evident by optical or mechanical unbalance in the system. All of the above phenomena are discussed in later sections of this report. And all are reduced by increasing the length.

Noise terms that limit the measurement of the time (phase) differences, the equivalent of the system transducer noise, are also divisible into fundamental terms and those that are reduced by technical improvements.

The ability to measure a small time difference (phase shift) is determined by the photon counting statistics at the photo detectors--the shot or Poisson noise--. The gravitational strain limit imposed by this noise is reduced by increasing the circulating light power and the light storage time in the antenna, in effect increasing the transducer gain.--the change of intensity at the photo detector per change of phase difference. When the power and storage time are increased to the point where the uncorrelated light pressure fluctuations on the masses become measurable, one has attained the quantum limit. At present and in the prospects for the first long baseline system, the light powers are sufficiently low that the Poisson noise is expected to dominate at high frequencies. The Poisson term in the low power limit does not depend explicitly on the antenna length but rather on the storage time, so that it is possible to reduce its effect by multiple reflection. One should bear in mind, however, that to gain a long storage time in a small antenna requires many beam transits which impacts on the complexity and quality requirements of the optics.

Other noise terms effecting the ability to measure small phase (time) differences include: laser frequency and amplitude fluctuations, the effect of light scattering, the interaction of antenna misalignments with laser beam position and angle fluctuations. None of these effects are fundamental and their importance is a strong function of the specific optical design. Different designs deal with these terms in varying ways as will become clearer in the section describing the prototype antennas.

A factor common to all designs is the necessity of a vacuum system. This requirement is driven by both classes of perturbing effects. A vacuum is needed around the masses to: reduce acoustic noise coupling, eliminate thermal gradient forces driven by gas pressure and to reduce gas damping which introduces thermal noise. A vacuum is also required along the light paths to reduce index of refraction fluctuations due to acoustic excitation and the fundamental thermally driven statistical column density fluctuations of a gas at equilibrium.

SOURCES OF GRAVITATIONAL RADIATION

1.0 Introduction

In this section of the report we present a review of the possible sources of gravitational radiation and of the nature of the signals they would produce. We will express the strength of the signal in terms of h (=2 $\Delta\ell/\ell$), the value of the metric perturbation (strain) at the antenna.

Gravitational radiation is produced by the time-varying gravitational field of a massive system. Monopole radiation is forbidden by the conservation of energy, while dipole radiation is forbidden by the conservation of momentum and angular momentum. Thus the lowest order of gravitational radiation allowed is quadrupole radiation. For most systems, this order dominates the gravitational luminosity, in which case the luminosity is given approximately by

$$L = \frac{G}{c^5} \langle \dddot{Q}^2 \rangle$$

where $\dddot{Q}$ is the third time derivative of the reduced quadrupole moment of the mass distribution. The flux at a distant point is given by

$$F = f\ (\theta,\phi)\ \frac{L}{4\pi D^2}$$

where D is the distance to the source and $f(\theta,\phi)$ is the radiation pattern (of order unity). The metric perturbation h is related to the flux by

$$F = \frac{c^3}{16\pi G} \langle \dot{h}_+^2 + \dot{h}_x^2 \rangle .$$

The chain of reasoning in making predictions about possible gravitational wave signals takes the following form: The astrophysicist considers a kind of source, and from a study of its dynamics is able to calculate the strength and temporal or spectral character of the gravitational radiation which it emits. (Often it is the case that the difficulty of this task lies less in the subtleties of general relativity than in the complexity of astronomical systems.) In addition, it is necessary to estimate the rate of occurrence (or density) of such sources in some fiducial volume, say a galaxy. For impulsive sources, one calculates a maximum likely signal strength by assuming that the source is located on the surface of a sphere (centered on the antenna) large enough to contain one event per month (or year, or however long an experimenter is able to wait). For periodic sources, one assumes the source is approximately $n^{-1/3}$ away from the antenna where n is the number density of sources. Of course, for known individual objects one uses the true distance away. The duration and frequency content (i.e. characteristic frequency, bandwidth) determine to some extent the experimenter's design of his apparatus and data analysis strategy. The expected signal strength, when compared with instrument noise levels, indicates whether it is likely that a successful detection can be made. Unfortunately the uncertainties in all of the dimensions of these predictions are large, so only very general guidance can be drawn from them.