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Gravitational radiation experiments at the University of Reading and the Rutherford Laboratory

W D Allen and C Christodoulides

Applied Physics Division, Rutherford Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK
and
Department of Engineering and Cybernetics, University of Reading, Whiteknights, Reading RG6 2AY, UK

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Abstract. The results are reported of a search for short pulses of gravitational radiation, using two split-bar detectors 30 km apart. The detectors have masses of 625 kg each and are capable of millisecond resolution over a broad band around 1200 Hz. Pulses imparting energy of $\frac{1}{2}$ to $1\,kT$ to each bar, and coincident within ±1 ms, were indistinguishable in trace characteristics from pulses due to thermal noise; and the number in the bin registering coincidences within ±2 ms (ie 308 in total), was indistinguishable from the numbers in bins of the same timewidth but registering coincidences with time differences of up to ±10 ms between the two detectors.

1. Introduction

After a decade of exploratory development, Joseph Weber announced that he observed coincidences between detectors designed to register gravitational radiation and situated 1000 km apart (Weber 1969). This, and a succeeding paper suggesting that the source was to be located at the centre of our Galaxy (Weber 1970), stimulated several groups to repeat the experiments (Logan 1973). Among them was our own, which started in 1970 and has now been operational for about a year. In common with the experimental groups other than Weber's, we have failed to detect any pulses which give energy to detectors 30 km apart, other of course than random noise effects at a level of about $\frac{1}{2}\,kT$. Our experiment is presented in greater detail elsewhere (Allen and Christodoulides 1975) and only a brief summary of the main results is given here.

2. Summary

2.1. Chief properties of the detectors

The detectors are located in relatively isolated huts, one near Reading (Sonning) and the other at the Rutherford Laboratory, separated by a distance of 30 km. Mechanically, the bars are of aluminium alloy, 46 cm in diameter and 150 cm long, with a total mass of 625 kg each. The construction follows the split-bar principle suggested by P Aplin of Bristol University: two cylinders, half the length of the 'bar', are cemented together via piezoelectric transducers at the plane of maximum strain (in contrast to Weber's detector which is a single 150 cm bar with transducers cemented around the periphery).

Two factors enter into the sensitivity of the system to mechanical impulses: β the ratio of the electrical energy in the transducers to the total energy in the bar, and Q the overall quality factor of the bar. As compared to a solid bar, our Q is naturally less by a considerable factor (about 20) due to mechanical losses in glue and transducers; but the value of β is much higher and the product βQ is about 10 times higher than that for the Weber detectors.

Electrically, the system is converted into a relatively broad-band (600 Hz bandwidth round a central frequency of 1180 Hz) detector by a notch filter (Drever 1971, paper presented at the International Conference on Gravitation and Relativity, Copenhagen; see also Buckingham and Faulkner 1972). The amplified outputs from the bar and from the filter are fed into a shift register (Drever *et al* 1973); when the filter output exceeds a threshold level the signal arrests the register. When this occurs at Sonning the contents of the register are then transmitted in digital form via a telephone link to the Rutherford Laboratory, and if there has been a trigger at the Rutherford detector, also within ±10 ms, the traces from both ends are displayed on an oscilloscope and photographed. Figure 1 shows some typical results from applied forces giving 1 kT to each bar simultaneously and from a typical random noise coincidence. The threshold was set at $\frac{1}{2}$ kT for the Rutherford Laboratory and 0·8 kT for Sonning. Calibration of the system, using timing pulses at 60 kHz from Rugby radio station, was carried out three to four times weekly for most of the period of operation.

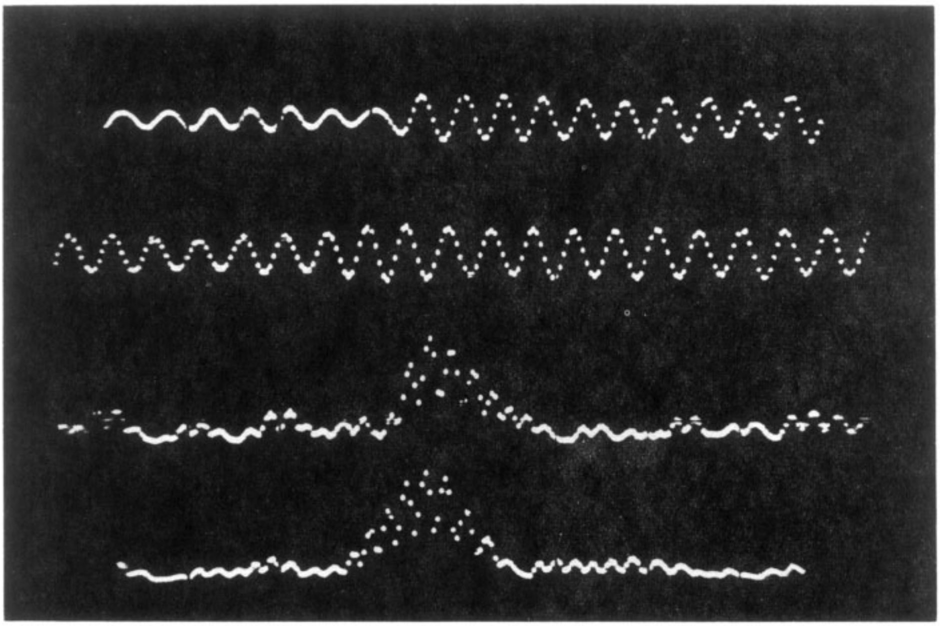
2.2. *Experimental procedure*

Random coincidences within ±2 ms were photographed at a rate of about 1 per day. The system also recorded coincidences in bins 4 ms wide, for a range of -14 to $+18$ ms delay between the Sonning pulses and those at the Rutherford Laboratory. The photographed coincidences (±10 ms) were timed to within ±1 s. No coincidences were observed which could be ascribed to gravitational radiation impulses. The histogram of coincidences between the eight bins showed no difference outside statistics between the bin recording prompt coincidences and the bins recording delayed coincidences. Neither was any preferred time found on a sidereal timescale for the occurrence of coincidences.

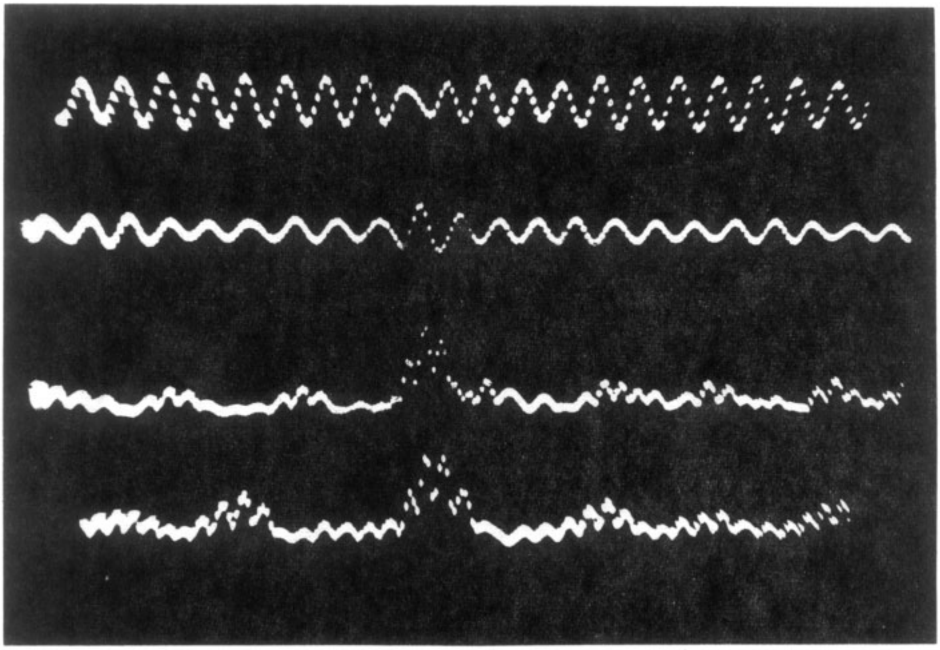
A brief account is given below of some of the problems encountered and of the techniques developed in the construction and operation of the bars.

3. Bar construction

Preliminary work was done on deciding which glue to use to avoid excessive losses which would drastically reduce the overall Q. Aluminium bars of 2 in diameter and 15 in length were cut at the middle and reassembled using the glue under investigation, by heating under compression. The mating faces were machined as flat as possible. Various glues were examined, such as black wax, pitch, sulphur, sulphur–pitch mixtures and Araldite (Devcon), before it was decided that PVA sheets, which could be kept as thin as 0·0005 in, had the advantage of low mechanical losses and enabled the construction and dismantling of bars at temperatures low enough (~120 °C) so as not to damage the transducers. Accordingly, the first bar (Sonning) was built using PVA as glue. Later, a glue was supplied to us by the Glasgow University group (of unknown nature, possibly Araldite CT-200 by CIBA-GEIGY, to be referred to as 'Glasgow glue'). This was found



(*a*)



(*b*)

Figure 1. Photographs of the signals from both detectors. In each photograph the top trace is AC voltage output of the Rutherford bar, the second trace is the same from Sonning, the third is the filtered and rectified signal from Rutherford, and the fourth is the same from Sonning. Each cycle corresponds to 0·85 ms. Time increases from left to right. (*a*) shows 1 kT calibration pulses applied to both bars; (*b*) shows a coincidence caused by the thermal noise of the bars.

to be even better than PVA and had to be heated only to about 100 °C to form strong bonds at low thicknesses. This glue was used in the construction of the second (Rutherford) detector.

Prototype split bars were also built to check the degree of agreement between theoretically predicted and actual values of frequency and β. The results were rather disappointing, the frequencies being about 20% lower than predicted and β's down by a factor of 2. There is evidence to suggest that the discrepancies in frequency are caused by the azimuthal distortion of the aluminium faces in contact with the transducers. The low β's could be due to a slight deterioration of the electromechanical coupling coefficient k_{33} after the heating, but as changes of k_{33} during heating runs were found to be no more than 10%, it is suspected that the actual value of k_{33} for the transducers used was lower than that claimed by the manufacturers. In any case the relevant electromechanical coupling coefficient should not be k_{33} but, due to the geometry of the transducers (fairly flat discs), it should lie between $k_{33} = 0{\cdot}64$ and $k_t = 0{\cdot}48$, the thickness coupling factor for laterally clamped transducers.

The two full-scale bars built were almost identical and only the Rutherford bar will be described, with data relevant to the Sonning bar given in brackets where they differ. The Rutherford (and Sonning) bar consists of two aluminium cylinders of total weight 625 kg, length 74 cm each and 46 cm in diameter. The two halves were joined by sandwiching between them seven glass–transducer assemblies, one at the centre and the others on a regular hexagon at a distance of 15 cm from the centre. The mating faces of the aluminium were lapped to flatness within ±0·0001 in. The glue used was 'Glasgow glue' (PVA for Sonning). The transducers were PZT8 (Gulton G1408) of diameter 5 cm and thickness 2·4 cm (1·9 cm). Insulation from the aluminium was provided by glass discs, one on either side of each transducer, of diameter 5·4 cm and thickness 0·32 cm. These glass–transducer assemblies were constructed first and were ground to uniform thickness and flatness to within ±0·00005 in, the thickness of all assemblies being identical within this limit.

For the construction of each bar the two aluminium cylinders with the transducer assemblies and glue layers held in position were heated to 100±10 °C for 20 hours for Rutherford or 165±5 °C for 28 hours for the Sonning detector. During heating, the bars were under compression along their axes, the aim being to reduce glue thickness. Forces of around 800 lbf were used, resulting in pressures of 30 psi on the glass–transducer faces. When cooling down, the two halves were kept at the same temperature within ±0·5 °C to avoid freezing in of any strains due to differential expansion, which would lead to relaxation noise or damage to the transducers.

The final parameters of each bar are as follows (Sonning in brackets): frequency $f_0 = 1181$ Hz (1173 Hz), quality factor $Q = 7000$ (3400), measured $\beta = 0{\cdot}03$ (0·02) and $\beta Q = 200$ (70). A year after construction Q deteriorated to 4000 (2000) due to changes in either the glue or the transducers.

To minimize noise due to seismic or acoustic pick-up and temperature variations, both bars were enclosed in steel vacuum tanks (under vacuum of roughly 10 μm), which were resting on four piles of concrete blocks and rubber sheets at the bottom of 6 ft deep pits. Inside the tank the bar is suspended by steel wires from the middle of each aluminium half, the whole suspension system hanging from a 3 in diameter spring which in turn hangs from a plate resting on a pile of seven lead discs of 45 lb weight, separated by rubber sheets of 9 in diameter and $\frac{1}{4}$ in thickness.

A search for resonances revealed a few due to the tank and the suspension system. The tank was coated with an $\frac{1}{8}$ in thickness of 'Aquaplas' (a colloid of rubber and plastics) and resonances in the steel suspension wires were damped by using pieces of rubber. The only troublesome resonances remaining were at 461 Hz and 3945 Hz; these were finally removed from the output by electronic filters.

4. Electronics and data handling

The transducers are connected all in parallel for the Rutherford bar giving a total of 4200 pF, and in a series combination of three groups consisting of 2, 3 and 2 transducers in parallel for the Sonning bar giving 950 pF. Their outputs are fed to low-noise FET preamplifiers situated inside the vacuum tanks and run on lead–acid batteries to avoid pick-up (figure 2). These preamplifiers were constructed by Professor E A Faulkner's group at Reading University, with FET's specially selected for low noise. Their ultimate noise voltage referred to input is 1 nV $Hz^{-1/2}$.

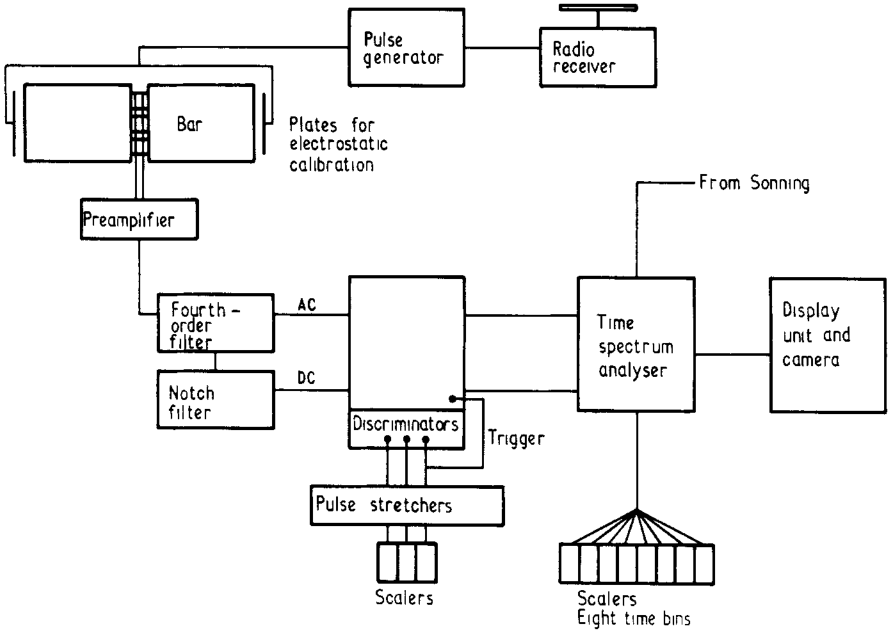


Figure 2. Block diagram of the system at the Rutherford Laboratory. That at Sonning is identical but without the time spectrum analyser, display unit, camera or the eight time scalers.

The preamplifier output (of the order of 1 mV) is then passed through a fourth-order filter which limits the bandwidth between 460 Hz and 4 kHz, at which frequencies the gain is almost zero to remove the two mechanical resonances left in the support system. Next, the signal is passed through a notch filter centred at the resonance of the bar to remove the resonance and give an overall broad-band response with a $Q_M \sim 5{\cdot}3$, as defined by Buckingham and Faulkner (1972). The expected signal sensitivity was close to the observed $\frac{1}{50}kT$ ($\frac{1}{30}kT$ for Sonning), this being the mean energy in the bar as observed through the transducers (ie mean energy in transducers divided by β).

The two detectors are 30 km apart and are connected via a data link. The rectified output of the notch filter is integrated with a time constant of the order of 1 s to provide a reference voltage level. When the rectified signal exceeds this by a predetermined factor, the system is triggered. When this happens at Sonning, the signal within ±20 ms of the trigger, sampled every 50 μs, is sent via the line, in digital form, to the Rutherford station. If after correction for the delay in the line, there has not been a trigger at the Rutherford end within ±10 ms of that at Sonning, the Sonning pulse is simply counted. If however there has been a trigger within ±10 ms, then the traces from both detectors, within ±10 ms of the Sonning trigger, are displayed on an oscilloscope screen and photographed (figure 1). A dial registering time in seconds is also photographed to time the event.

In addition the event is classified in one of eight bins, each of 4 ms width, depending on the time difference between the two triggers. All but the central prompt coincidence bin provide a random coincidence rate since any gravitational coincidence should be well within ±2 ms, considering the fast response of the system.

The discrimination levels are set so as to have about one pulse per minute from Sonning (dictated by the total transmission time of 1·7 s for each 40 ms event), and about 10 pulses per minute at the Rutherford Laboratory. These rates lead to about one coincidence per day in each of the eight 4 ms bins. The discrimination levels correspond to energies of 0·5 kT and 0·8 kT for the Rutherford and Sonning detectors respectively.

Both detectors are calibrated in coincidence three to four times per week. To achieve this, two 60 kHz radio receivers are used to provide triggering pulses at 1 s intervals, as received from the Rugby station. These then trigger pulse generators which apply standard −20 V pulses of 0·42 ms duration on electrostatic plates (12 in diameter and at 6 mm distance from the bar ends). These give energy of 1 kT to each bar, and have been checked to be synchronous to within about 0·1 ms. The outputs of each bar are photographed at the beginning of each film to provide a record of sensitivity and synchronization (figure 1).

As a guide to rejecting pulses due to electrical pick-up, the AC output of each bar is also displayed and photographed in addition to the filtered and rectified output (figure 1). In this way spurious pulses which were seen to have left the energy of the bar unchanged were rejected. The rate of such spurious pulses was found to be about one per 10 h at each end.

5. Results and conclusions

The system has been in operation for $1\frac{1}{2}$ yr. Data were collected for the last 11 months with an observation efficiency of 63 % giving a total observation time of 7 months. This time was found to be evenly distributed on a sidereal histogram of 12 1 h bins. The same was found to be evenly distributed on a sidereal histogram of 12 1 h bins. The same was found to be true for solar time provided that bins 12 h apart were added together.

A total of 2583 events were counted in the eight time bins, of which 1614 of coincidences within ±10 ms were photographed. The distribution in the eight time bins is given in figure 3(*a*). There were 308 coincidences within ±2 ms (bin 4) of which 167 were found from photographic analysis to have been coincidences within ±1 ms. A histogram of these against sidereal time is given in figure 3(*b*). No significant excess above average was found as indeed was the case for similar histograms of coincidences

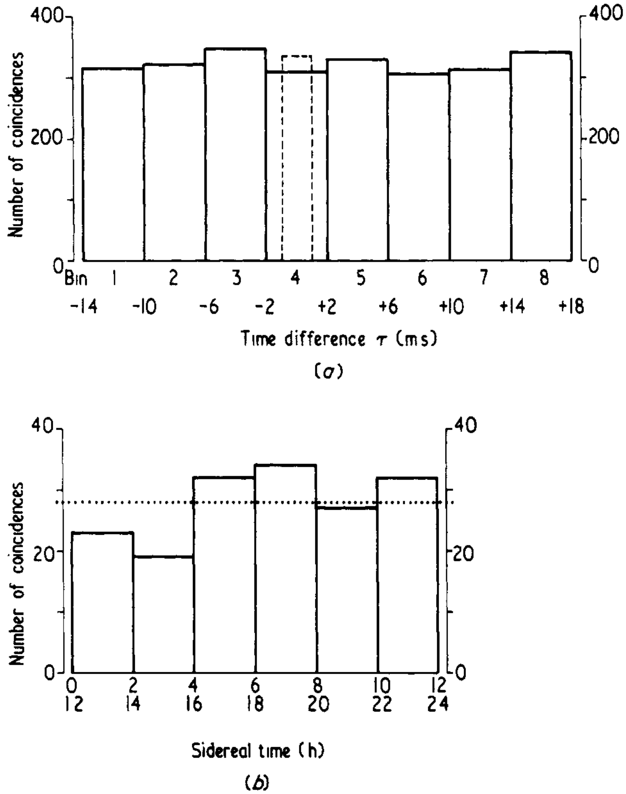


Figure 3. (*a*) Coincidence with time differences between the two pulses ranging from −14 to +18 ms (average 324). A total of 2583 were observed of which 308 were within ±2 ms. Also shown are the coincidences within ±1 ms, 167 in total. (*b*) The 'prompt' coincidences (within ±1 ms) arranged in a sidereal time histogram (average 28). Bins have a width of 2 h and those differing by 12 h were added together.

within ±0·5 ms or ±2 ms. Sidereal and solar times differed by up to 21 h during the experiment and any excess of pulses from one direction in space should have been apparent.

All pulses photographed were below roughly 1 *kT* except for some spurious ones (~10) which were rejected either because they did not coincide with a pulse from the detector within ±1 ms or as electrical interference identified as described in § 2.

Allowing for the lower masses of our detectors as compared to Weber's, we can say that the discriminator levels used correspond to about 1 *kT* on Weber's scale. It has to be concluded that at this level no statistically significant excess of coincidences was observed which could be due to gravitational radiation. If there are some such coincidences obscured by statistical variations between bins in the histogram of figure 3(*a*), their rate must be less than 1 per 12 days. In an analysis of the energy sensitivity of Weber's system (Christodoulides 1975; see also for examination of sources of noise and optimization of frequency bandwidths and discrimination thresholds), the discrepancies between our results and those of Weber *et al* (1973) are discussed further. The main conclusion, as illustrated by figure 3(*a*), is that the coincidences, coincident within 1 ms, are indistinguishable in trace characteristics from those in adjoining bins, representing delays up to ±10 ms, while the numbers registered in the 'coincident' bin are statistically consistent with the number registered in neighbouring bins.

As stated in the introduction, negative results have been previously reported by several groups. These groups vary in experimental techniques and methods of calibration, and detailed comparison is not justified. As will have been gathered from the foregoing, our experiment has in general followed the pattern of the Glasgow group (Drever *et al* 1973). The overall sensitivity to gravitational radiation is comparable: our sensitivity, in terms of kT, is one half that of the Glasgow detectors, but the mass is roughly twice as great. The chief difference is that our two detectors are 20 miles apart, rather than being housed in the one laboratory as at Glasgow.

We must conclude that unless Weber is detecting pulses of a narrow spectrum and near his frequency of 1661 Hz, all attempts to verify his claims of gravitational radiation have failed.

6. Acknowledgments

In this work we have been greatly assisted by R D Downs of the Rutherford Laboratory who designed and supervised the construction of the link, and by two research students, D Munro and J Whitney in the maintenance of the link. The amplifier and notch filter were provided by Dr M J Buckingham and Professor E A Faulkner of Reading University. Dr Buckingham also contributed to the work during the first year. We acknowledge support in part from the Science Research Council.

References

Allen W D and Christodoulides C 1975 *Gravitational Radiation Experiments at the Unviersity of Reading and the Rutherford Laboratory* Reading University Report

Buckingham M J and Faulkner E A 1972 *Radio and Electron. Engr* **42** 163–71

Christodoulides C 1975 *Sensitivity of Gravitational Power Detectors* Reading University Report

Drever R W P, Hough J, Bland R and Lessnoff G W 1973 *Nature, Lond.* **246** 340–4

Logan J L 1973 *Phys. Today* **26** 44–50

Weber J 1969 *Phys. Rev. Lett.* **22** 1320–4

—— 1970 *Phys. Rev. Lett.* **25** 180–4

Weber J, Lee M, Gretz D J, Rydbeck G, Trimble V L and Steppel S 1973 *Phys. Rev. Lett.* **31** 779–83