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# Resonant Detectors for Gravitational Waves

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The principles of the gravitational wave detection by means of resonant antennas are illustrated and a review of the resonant antenna experiments in the world is given. Possible plans for the future resonant antennas are indicated.

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## 1. INTRODUCTION

The experiments for the search of gravitational waves started in the early sixties with Joseph Weber at the University of Maryland, bringing the problem of g.w. into the domain of observable physical phenomena.

The detection technique has been enormously improved during the last thirty years, and further remarkable steps can be foreseen in the near and far future. The sensitivities reached today differ by slightly more than two orders of magnitude in amplitude from those estimated to be necessary for the detection of g.w. signals originating from various astrophysical sources expected to have satisfactory statistical occurrence.

The discovery of g.w. would open a new window on the Universe, in particular a new approach for the investigation of stellar collapses and of possible deviations from perfect symmetry of bodies such as the pulsars. Also some experimental information connected with the string theory of the Universe could be obtained.

In what follows we will be concerned only with the search of g.w. using resonant detectors.

## 2. THE RESONANT ANTENNA

As far as the g.w. sources, we limit ourselves here to considering the  $h$  value at the Earth of a g.w. burst generated at distance  $R$  due to the conversion in g.w. of an amount of matter with mass  $M_{gw}$ .

$$h \approx \frac{1}{R\omega_g} \sqrt{\frac{8GM_{gw}}{c\tau_g}} =$$

$$3.11 \cdot 10^{-20} \frac{10\text{Mpc}}{R} \sqrt{\frac{M_{gw}}{M_0}}$$

$\tau_g=1$  ms is the assumed duration of the g.w. burst and  $\nu_g$  is the antenna resonance frequency, about 900 Hz. If the source is located at the center of our Galaxy we obtain for  $M_{gw}=10^{-2}M_0$  :  $h \sim 3 \cdot 10^{-18}$ . If the source is located in the Virgo Cluster we get  $h \sim 3 \cdot 10^{-21}$ .

The resonant detector is, typically, a metallic cylindrical bar, usually of high quality aluminum alloy (for the Perth experiment the material is niobium, which has higher  $Q$ ). For capturing as more energy as possible from the g.w. the mass of the bar needs to be as large as possible. The LSU-Rome collaboration uses bars 3 m long, weighting about 2300 kg. When the bar is hit by a g.w. burst with amplitude  $h(t)$  and very short duration  $\tau_g$  impinging perpendicularly to its axis, it starts to vibrate at those resonance modes that are coupled to the g.w. The odd longitudinal modes are the most coupled ones. The first mode has frequency  $\nu_0=\pi v/L$ , about 900 Hz for the above considered bar ( $v=5400$  m/s is the sound velocity in aluminum).

The energy  $E$  captured by the bar at the first longitudinal resonance mode can be calculated by means of the cross-section  $\Sigma$

$$E = \Sigma f(\omega_0)$$

$$\Sigma = \frac{8}{\pi} \left(\frac{v}{c}\right)^2 \frac{G}{c} M \sin^4 \delta \cos^2 2\Psi$$

where  $f(\omega_0)$  is the spectral energy density [joule / (m<sup>2</sup> Hz)] of the incident g.w.,  $\delta$  is the angle between the bar axis and the direction of the source,  $\Psi$  is the angle between the polarization plane and that formed by the bar axis and the direction to the source. We notice that the cross-section increases with the mass and with the square of the sound velocity. Aluminum is a good material which has high sound velocity and low cost, but one might think to find a better material.

The resonant detector measures the Fourier component  $H(\omega_0)$  of  $h(t)$  at the bar resonance. In the rough approximation  $H(\omega_0) = h(t) \tau_g$  we derive the value of  $h$  belonging to the g.w. burst that releases in the bar the energy  $E$

$$h = \frac{1}{\tau_g} \frac{L}{v^2} \sqrt{\frac{E}{M}}$$

The bar vibrations become electrical signals by means of proper electromechanical transducers. The transducers, which we shall not discuss here, represent the most delicate part of the experiment and still need to be considerably improved.

The electrical signal from the transducer is amplified and then processed by means of optimum filters in order to make the signal to noise ratio as large as possible. It can be shown that if one looks for signals due to short bursts of g.w. as described above, then the minimum vibration energy of the bar that can be detected with SNR=1 is, in a simplified treatment,

$$E_{\min} = kT_{\text{eff}} = kT / \beta Q + 2kT_n$$

where  $T_n$  is the noise temperature of the electronics,  $T$  is the bar temperature,  $\beta$  is the fractional part of energy available to the amplifier and  $Q$  is the quality factor of the entire apparatus.  $T_{\text{eff}}$  is called the effective noise temperature and represents the sensitivity for short bursts. It is clear that  $T$  and  $T_n$  must be as small as possible and  $\beta Q$  must be large. As far as  $T_n$  a FET amplifier can have, at best,  $T_n \approx 0.1$  K. The SQUID amplifiers could go down to the quantum limit, that is  $T_n \approx 6 \cdot 10^{-8}$  K, but it is extremely difficult to properly match this very low noise amplifier to the transducer. By lowering the bar temperature to  $T=40$  mK, with  $\beta Q \approx 10^6$  and  $T_n \approx 10^{-7}$  K one could get  $T_{\text{eff}} \approx 2 \cdot 10^{-7}$  K, that is  $E_{\min} = 2 \cdot 10^{-30}$  joule. Putting  $E = 2 \cdot 10^{-30}$  joule we obtain  $h \approx 3 \cdot 10^{-21}$ . This should allow to observe the collapses in the Virgo Cluster.

The real problem is that, although all techniques appear available, their implementation on the actual experimental set-ups requires new technology and, in all cases, very long times.

### 3. REVIEW OF THE PRESENT DETECTORS

In the following table we give a summary of the present resonant detectors. The temperature  $T$  indicates which detector is operating at liquid helium temperatures. The date of the data taking indicates the initial time of the operation, although sometimes the detector operation has been interrupted for various periods due to maintenance or upgrading of the apparatus. Finally the sensitivity refers to a g.w. burst lasting 1 ms, except for the Tokyo group which is searching for the continuous g.w. due to the CRAB pulsar. For Nautilus and Auriga the sensitivity is not given, as they have not yet been fully tested.

We remark that  $h = 7 \cdot 10^{-19}$  corresponds to a g.w. burst due to the total conversion of about  $10^{-4}$  solar masses in the Galactic Center.

Table 1  
Resonant antennas in the world.

	M [kg]	T [K]	Amplifier	data taking	sensitivity h
Louisiana ALLEGRO	2300	4.2	SQUID	June 1991	$7 \cdot 10^{-19}$
Rome : EXPLORER	2300	2.5	SQUID	July 1990 (1986)	$7 \cdot 10^{-19}$
NAUTILUS	2300	0.1	SQUID	1994-1995	$3 \cdot 10^{-18}$
ALTAIR	390	4.2	SQUID		
Legnaro AURIGA	2300	0.1	SQUID	1995	
Moscow University	1500	290	tunnel	1993	$7 \cdot 10^{-17}$
Tokyo (CRAB)	1200	4.2	parame- tric	1991	$2 \cdot 10^{-22}$ monochromatic
Perth NIOBE	1500	4.2	parame- tric	June 1993	$7 \cdot 10^{-19}$

#### 4. EXPERIMENTAL RESULTS

The gravitational wave antennas Allegro of the LSU group and Explorer of the Rome group have recorded data simultaneously from 24 June 1991 to 16 December 1991 for a period of about 180 days. The antennas were aligned parallel to each other, so the same gravitational wave burst would have produced in the two antennas signals with the same amplitude. Each group performed its own filtering on the data of its own antenna, both filters aimed at the detection of short bursts of gravitational radiation. The filtering procedure gives the energy innovations, which we call also events. Both Allegro and Explorer have thresholded these events such to select about 100 events per day. This corresponds to consider only events with energy of the order of 80 or 100 mK (a few times the effective noise temperature), corresponding to values  $h \approx 2.5 \cdot 10^{-18}$ .

While the data analysis is still underway, we report some preliminary result (see [1]).

We show in Fig. 1 the number of coincidences and the accidentals as function of the event energy for a window of  $\pm 1.5$  seconds. We notice some coincidence excess, but the statistical significance is small because the coincidence window was chosen such to maximize the coincidence excess. We notice also that there are no coincidences for energy greater than 180 mK. Thus we might conclude that our search for gravitational wave bursts in the above period of time, able to produce in the antennas signals with energy larger than 180 mK, has

given a negative result.

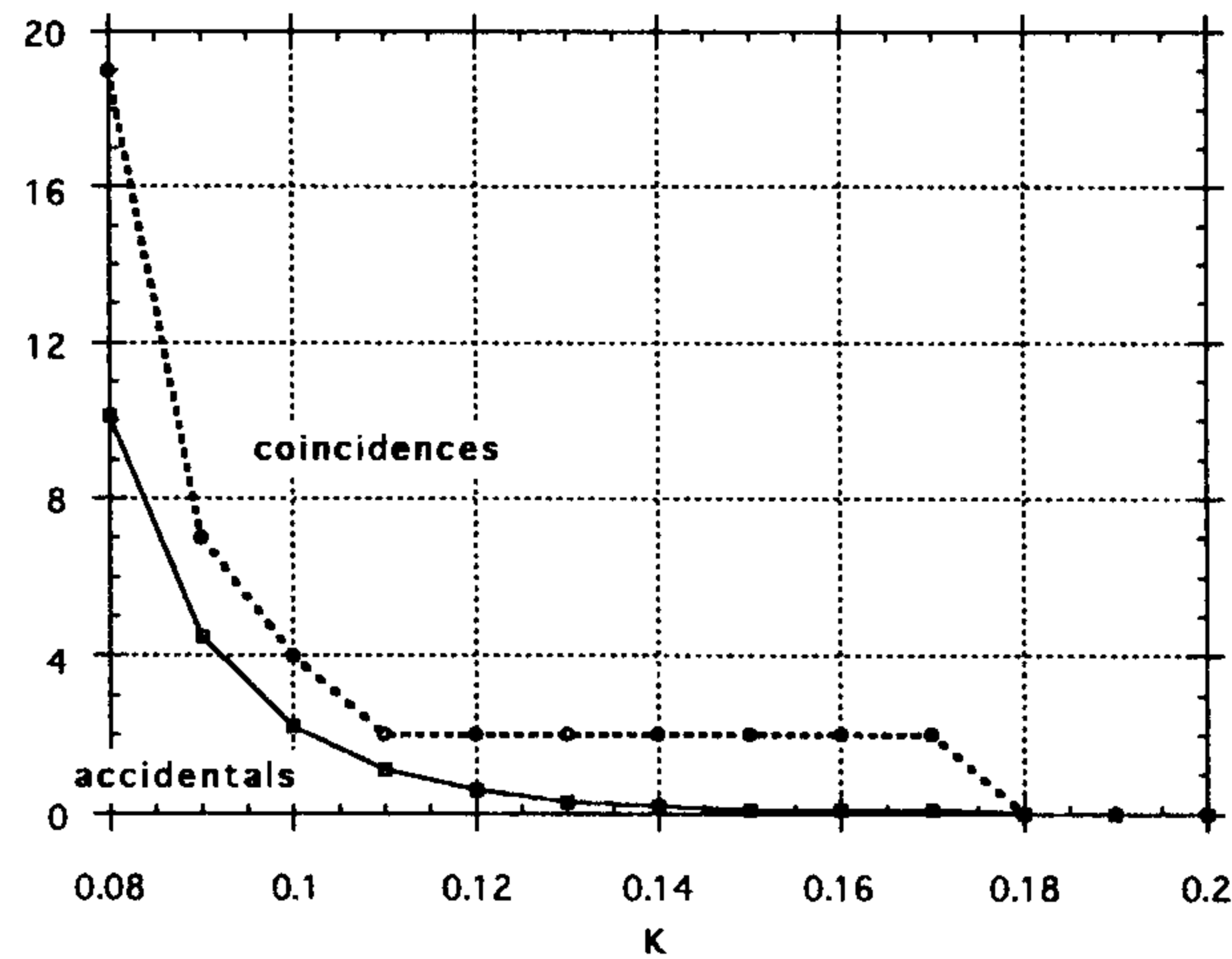


Fig. 1 – Coincidences between Allegro and Explorer for a window of 1.5 s.

## 5. NEW PROJECTS

In order to improve the sensitivity of the resonant detectors we must start by examining the formula which gives the cross section. The free parameters are: the mass  $M$ , the sound velocity  $v$  in the bar material and the orientation with respect to the (unknown) source. One could also consider the detector dimension which gives the resonance frequency and adjust such a frequency to that of the expected g.w. sources. But we prefer not to consider it, because of the physicists extreme ignorance of the matter, and we prefer to follow the Weber-Fairbank philosophy, to make the cross-section as large as possible. As matter of fact the presently operating antennas in all laboratories have the largest possible dimensions. On the basis of these considerations there are at present two lines of development.

- a) Many cylindrical detectors. One observatory made with  $n$  cylindrical detectors, each one with mass  $M$ , has a sensitivity that is proportional to the total mass  $nM$ . Orienting the cylinders properly [6] one takes care of the sin and cos terms, thus allowing to detect waves with any direction and polarization. Six bars, installed in proper places on the world, should cover all possibilities.
- b) Two spherical detectors. This new approach [7] has been recently considered by most of the groups considered in section 3 (as well as two other groups, one in Brazil and the other one in Holland) and appears to be possible with the help of new technologies that allow to construct detectors as large as wished (but this has to be proven yet experimentally). The spherical detectors have, basically, two advantages with respect to the cylindrical detectors: i) it is possible to use much heavier antennas, since an aluminum sphere with a diameter of 3 m weights 38 tons, against 2.3 ton of the available 3 m long cylinders; ii) one spherical detector is sensitive to gravitational waves coming from all directions and with any degree of polarization provided has been equipped with six displacement transducers. In fact, one sphere is equivalent to 5 bars properly oriented on the Earth surface, each one with the mass of the sphere. Conservative estimation of the

sensitivity of a 3 m sphere resonating at 1000 Hz is  $h \approx 7 \cdot 10^{-22}$ , while the best interferometers in the most advanced stages have, at 1000 Hz, a sensitivity of  $4 \cdot 10^{-22}$  only if the gravitational wave arrives with the optimum direction and polarization. Another advantage of a spherical detector is represented by the larger cross-sections at higher harmonics [8], as respect to the cylindrical detector. This allows to use a spherical detector as a xylophone with frequencies ranging, roughly, from 1 to 5 kHz. This feature turns out to be important not only because provides a signature of the g.w. signal but also because it allows to study the stochastic background of gravitational waves.

On the other hand, whilst the spherical detector still needs a careful feasibility study, the cylinders have the advantage to have been already developed.

As far as the sound velocity, we still lack a complete study of the various possible materials. A material better than aluminum would be of benefit to both cylinders and spheres.

## REFERENCES

1. Z.K.Geng et al. "Operation of the Allegro detector at LSU", First Edoardo Amaldi Conference on Gravitational wave Experiments, Frascati, 14-17 June 1994.
2. P.Astone et al. "Long-term operation of the Rome Explorer cryogenic gravitational wave detector". *Physical Review D* **47**, 2, January (1993).
3. P. Astone et al. "The Nautilus experiment" First Edoardo Amaldi Conference on Gravitational wave Experiments, Frascati, 14-17 June 1994.
4. M.Cerdonio et al. "Status of the Auriga gravitational wave antenna", First Edoardo Amaldi Conference on Gravitational wave Experiments, Frascati, 14-17 June 1994.
5. D.G.Blair et al. "Operation of the Perth cryogenic resonant-bar gravitational wave detector", First Edoardo Amaldi Conference on Gravitational wave Experiments, Frascati, 14-17 June 1994.
6. M.Cerdonio et al., *Phys. Rev. Lett.* **71** (1993) 4107.
7. E. Coccia "Spherical Gravitational Wave Detectors", *Les Rencontres de Physique de la Vallee d'Aoste: Results and Perspectives in Particle Physics* La Thuile, March 1994.
8. E. Coccia, A.Lobo, J. Ortega, *Phys. Rev. D* **52**, 3735 (1995).