THE SEARCH FOR GRAVITATIONAL WAVE WITH RESONANT DETECTORS

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I review some of the features of Resonant Gravitational Wave Antennas, with attention to the issues of sensitivity and bandwidth, and to the main technological keypoints that take part in determining the performance of present and future detectors. After a brief inventory of the antennas presently operating in the world, I present some recent experimental results of the Roma group relative to the search of bursts, periodic and stochastic radiation. Finally, I discuss the avenues that can be taken to increase sensitivity of these detectors.

1 Introduction

While preparing this paper, I have wondered whether gravitational waves (g.w.) should belong in the topic of this workshop: are we dealing with ***very high energy phenomena*** ? Indeed, if we consider the processes that lead to generation of g.w., they are undoubtely among the most energetic events the Universe can witness: to give an example, consider a supernova explosion that radiates 10^{-3} solar masses into g.w.: the emitted energy, measured in the units most familiar in this workshops, would be about $10^{63}eV$! Should such an event take place at the center of our galaxy, we would receive on the Earth a g.w. fluence of $10^{21}eV/m^2$, i.e. a flux of about $3 \cdot 10^{24}eV/m^2/s$ in about one ms. On the other hand, I will focus on the process of detection of this radiation that lies at the opposite end of the energy scale: present antennas are today capable of detecting a change in energy of the order of 3 mK, i.e. $10^{-7}eV$: and we are talking of the vibrational energy of a solid of more than 2 tons of mass, i.e. the of collective motion of an ensemble of about 10^{30} atoms. Yet, this sensitivity is probably barely sufficient to detect only large galactic events such as the above example. This is due to the extremely small coupling of g.w. to matter, orders of magnitude smaller than neutrinos, that makes our detectors (and the whole Earth) almost transparent to g.w.

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This is why gravitational waves still elude direct detection, more than three decades after J.Weber's initial experiments [1] with room temperature detectors. Time, however, did not pass invain, as slow but steady progress in detector technology has brought us to having four detectors simultaneously on the air, each with energy sensitivity over 1000 times better than Weber's first antennas, and long interferometric antennas that are soon to begin operation in a complementary frequency range.

We begin this review, for completeness, by recalling the concept of g.w. detection by resonant antennas [2]: the incoming wave induces a vibration in a solid elastic body (the antenna); this vibration must be detected, against the background noise due to thermal motion of the body itself and to the wide band noise of the readout amplifier. This task is easier (rather, less difficult) if detection is carried on a resonance (for larger response) of a high Q oscillator.

The fluence sensitivity of a resonant detector to short bursts of g.w. is described by the expression:

$$F(f) = \frac{\Delta E_{min}}{\Sigma f(\theta, \phi)} \tag{1}$$

where ΔE_{min} is the minimum detectable energy change in the antenna, Σ is the cross section and $f(\theta, \phi)$ is the radiation pattern, i.e. a factor ≤ 1 depending on the wave direction and polarization state. In the last two decades experimental work has been carried out on cylindrical Al bars, all of the same dimensions (with one exception), so that Σ and $f(\theta, \phi)$ were fixed, and most improvements, that we shall review in the first part of this paper, have taken place in reducing ΔE_{min}. In the last section, however, we shall briefly examine recent developments aimed at improving also the cross section Σ and the radiation pattern $f(\theta, \phi)$.

2 Sensitivity

The minimum detectable energy ΔE_{min} or, as we like to say, the detection noise temperature $T_{eff} = \Delta E_{min}/k_B$, has been, for a long time, the standard figure of merit for assessing the sensitivity of bar detectors; however, in the last year, there has been a growing consensus toward replacing this figure with a more complete description of the detector behaviour: the equivalent noise strain spectrum $S_h(f)$, that is the measured noise spectrum referred to the antenna input. It is formally defined via the Signal to Noise Ratio SNR :

$$SNR = \int df \frac{|H(f)|^2}{S_h(f)} \tag{2}$$

where $H(f)$ is the Fourier Transform of the g.w. amplitude h(t).

Use of $S_h(f)$ uniforms the way of describing sensitivity to the standard adopted in the community of interferometric antennas. Besides, it has the advantage of being less burst oriented than ΔE_{min} (and than its predecessors GPU and h_{min}). that measure the response to a short burst by integrating contributions to SNR over all frequencies. $S_h(f)$ instead describes sensitivity at each frequency: assuming it is non zero only over a band Δf, we can relate it to the older ways of assessing sensitivity:

$$h_{min} = \frac{1}{\tau_g}\sqrt{\frac{S_h(f_o)}{2\pi\Delta f}} \tag{3}$$

$$\Delta E_{min} = \frac{S_h(f_o)}{\Delta f}\frac{2v_s^4}{\pi M_a L^2} \tag{4}$$

where M_a is the antenna mass and v_s the speed of sound. On the other hand, $S_h(f)$ is also suited to describe sensitivity to periodic waves, of duration $\tau_g >> \Delta f^{-1}$

$$h = \sqrt{\frac{2S_h(f)}{t_m}} \tag{5}$$

where t_m is the observation time, and to stochastic waves: a stochastic background [3] (e.g. of cosmological origin) of g.w. with an energy density ρ_{gw} would cause on the antenna a strain with a spectrum:

$$S_h(f) = \frac{2G}{3c^2\pi f^3}\rho_{gw} \tag{6}$$

so that a measurement of the noise spectrum S_h of the antenna sets an upper limit on the g.w. energy density at that frequency.

The noise sources that contribute to the overall spectrum (electronic noise, antenna and transducer thermal noise, amplifier back action) appear at different location in the detector, and therefore have different transfer functions to the input: for this reason S_h has a complex spectral shape, that expresses how the antenna sensitivity varies as we move away from resonance (see fig. 4). For most purposes, it is however sufficient to give the value on resonance, that has a simple expression:

$$S_h(f_o) = \frac{2k_BTL^2}{v_s^4 M_a\tau} \tag{7}$$

and the FWHM bandwidth

$$\Delta f = \frac{f_o}{Q}\frac{4k_BT}{\Delta E_{min}}. \tag{8}$$

Every detector employs a resonant transducer i.e. a light mass oscillator that acts as an impedance matching device: it is mechanically coupled to the antenna (so that mechanical energy is transferred with signal amplification) and electrically coupled to a low noise amplifier. The challenge of achieving a lower ΔE_{min} lies mostly in designing and making a better transducer-amplifier readout system. For an antenna equipped with a resonant transducer, the resonance is split in two normal modes, each with the same bandwidth of eq. 8 and twice the S_h of eq. 7.

2.1 Bandwidth

A resonant detector is not an intrinsically narrow band antenna: it is useful to stress this concept, although it has been known for over 10 years [4]: an antenna dominated by thermal noise has, in principle, infinite bandwidth: indeed thermal noise and g.w. signal act on the detector in the same way, and appear at the output through the same transfer function (i.e., the antenna resonance): therefore their ratio is a constant independent of frequency. The presence of amplifier noise, which has a white spectrum, modifies this picture: the response to a g.w. (and to thermal noise) is visible only near resonance, where it can peak above the white amplifier noise. The width of this region is given by the relative strength of these two noise sources, and can be summarized by eq. 8, where the second term, that multiplies the intrinsic resonance width, is of the order of several hundreds. The use of a resonant transducer does not modify this picture, although in practice it improves it quantitatively.

In a well designed transducer, the resonating mass m_t is optimized as a function of three antenna parameters: mass M_a, thermal noise k_BT, decay time τ, and two transducer parameters: amplifier noise v_n and electromechanical responsivity $\alpha(V/m)$:

$$m_t = \frac{4\alpha}{\omega^2 v_n}\sqrt{k_BTM_a/\tau} \tag{9}$$

this equation can also be read by considering m_t as the impedance matching element between the antenna mass M_a and an "amplifier mass" ($\frac{16\alpha^2}{\omega^4 v_n^2}\frac{k_B T}{\tau}$). For such an optimized detector we have the best sensitivity and bandwidth:

$$\Delta E = k_B T_{eff} = 8\sqrt{\frac{v_n}{\alpha}} M_a^{1/4} \left[\frac{k_B T}{\tau}\right]^{3/4} \tag{10}$$

$$\Delta f = \frac{1}{2\pi}\left[\frac{2\alpha}{v_n}\right]^{1/2}\left[\frac{k_B T}{M_a \tau}\right]^{1/4} \tag{11}$$

For first generation, room temperature detectors, T_{eff} was of the order of $10K$ (with an improvement, due to filtering, of a factor 30 over average thermal noise). Present cryogenic antennas, reviewed in the next section, have reached a peak $S_h(f_0) \simeq 3 \cdot 10^{-43} Hz^{-1}$ or a $T_{eff} \sim 3 - 10mK$ (300- 1000 times better than T), over a band of about 1 Hz (to be compared with resonance width of less than a mHz). The minimum value of g.w. amplitude for a short (1 ms) burst is $h = 6 \cdot 10^{-19}$, corresponding to an amplitude of vibration of the cylinder end faces of $\delta x = 10^{-18} m$. Improvements in transducer technology should extend the bandwidth to about 20 - 50 Hz and reduce T_{eff} to $\sim 10^{-5} K$ and better in the next few years.

3 Detectors in operation

Four cryogenic g.w. antennas are presently in observation in the world, and a fifth is expected to begin operation in 1997.

All detectors, except Niobe, have a number of common features, some directly derived from Weber's original experiments:

—They employ a cylindrical bar of a high Q Alluminium alloy (Al 5056), 3 m long and 0.6 m in diameter, for a total mass $2M_a = 2300kg$ and a resonant frequency $f_o \simeq 915Hz$ at low temperature.

— The motion sensor is based on a mechanical resonator that uses the first flexural mode of a disc supported at its center ("mushroom" mode). Vibrations of this disc against a constant electric[5] or magnetic [6] field produce an a.c. signal that is detected by a d.c.SQUID superconducting amplifier.

—The innermost stage of vibration isolation consists of a U-shaped cable that supports the bar by its middle section, although other, outer stages are substantially different.

-ALLEGRO[7] is built and operated by the Louisiana State University group, led by W. O. Hamilton. The antenna is kept at 4.2 K in an all alluminium cryostat, but the suspension system hangs from room temperature, with no contact to the boiling cryogens. The bar motion is monitored by an inductance modulation transducer followed by a commercial Squid. It has been on the air since 1991, at a noise level $T_{eff} = 10mK$.

-EXPLORER[8] has been built and operated at CERN by the ROG Collaboration of the Roma group, led by G.Pizzella. It is mantained at an operating temperature of T=2.6 K by a large bath of superfluid Helium. The transducer consists of an Al mushroom of $M_t = 340g$, coupled to an electrostatic field of $2.6MV/m$. This capacitive signal source relies on a large superconducting transformer (turn ratio $N \simeq 5000$) to match a a specially designed d.c. SQUID[9].
It operates routinely at a sensitivity $T_{eff} \simeq 10mK$, comparable to that of Allegro.

-NAUTILUS [10] is the other detector of the Roma group, located at the INFN Frascati National Labs. and is the first antenna of the so-called "third generation", designed and built to operate at ultralow temperature. This requires a powerful dilution refrigerator and a complex cryostat, consisting of 7 nested containers: the 3 innermost Cu shields hang from each other on cables, to serve also as final stages of the suspension system. The antenna hangs from a Cu cable (rather than Ti, as in Explorer) to provide a high conductivity heat path to the

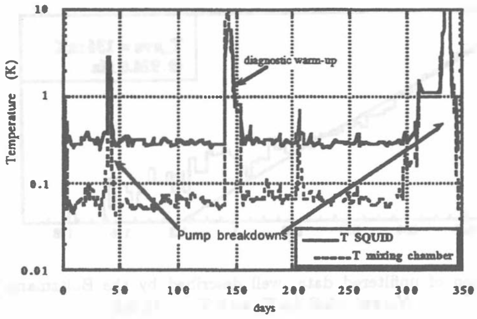

Figure 1: Temperature of the Nautilus detector during 1996: some short warm ups are indicated with their cause

refrigerator mixing chamber. This set up has proven highly successful in cooling the antenna in few days [11] and in keeping it at a temperature of 0.1 K for long time (14 months at the moment of writing, and counting, see fig 1). The readout of Nautilus is identical to that of Explorer. Although Nautilus is still in the development stage, as both the quality of data and the duty cycle improve steadily with time, it has already achieved some impressive results, like a record noise temperature $T_{eff} = 3mK$, approaching the target figure of 0.5-1 mK, depending on SQUID noise. Nautilus is equipped with a large cosmic ray telescope[12] that will serve as a veto against acoustic pulses generated in the bar by extended air showers or very energetic single hadrons. At the present level of sensitivity only a few cosmic rays generated events per week are expected, but their rate is bound to increase (up to about 2000 per day) as the noise level of the detector is pushed toward the quantum limit.

-AURIGA [13] is a twin detector to Nautilus (except for a few differences in the readout), built at Legnaro National Labs. of INFN by a local group led by M.Cerdonio.It features an auxiliary cryostat to retrieve and substitute electronics without warming up the whole antenna. After a rather successful diagnostic cool down, it should begin operation during 1997.

- NIOBE [14] The antenna developed by the research group at the University of Western Australia, led by D.G.Blair, has some features that distinguish it from all others: the resonator is a cylinder, like all existing antennas, but it is made of Niobium, a material chosen for its high density and Q ($\sim 10^8$); it is not suspended on a cable, but rests on a special four point support that fits on a suspended craddle; the auxiliary oscillator of the resonant transducer consists of a bending flap, to the end of which a small microwave cavity is fastened; the e.m. field, generated by a sophisticated, ultrastable Sapphire oscillator, is fed to, and read out from the cavity via a radiating, non contact coupling. This advanced technology readout allows them to achieve an energy sensitivity $T_{eff} \simeq 3mK$ at the frequencies $f_+ = 711Hz$ and $f_- = 689Hz$ without using ultra low temperatures. This figure, about 3 times better than Allegro's and Explorer's, makes up for the smaller cross section due to smaller mass and sound velocity (see eq. 14 below). Therefore it is interesting to note that all detectors routinely operating end up having similar fluence (and $S_h(f_o)$) sensitivity, despite the differences in design and technology.

4 Calibration and data collection

In this section I shall focus on the procedures used on, and results obtained by the Explorer and Nautilus antennas, although similar considerations can be made for the other two operating antennas.

A g.w. detector must produce *clean* data of *known amplitude*. *Clean* means that both the sampled data and the filtered data must follow the Boltzmann statistical distribution correspond-

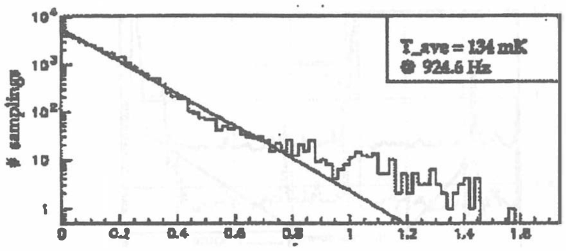

Figure 2: Energy distribution of unfiltered data, well described by the Boltzmann distribution $xN(\Delta E) = N_0 exp(-\Delta E/k_B T)$ with T = 111 mK .

ing respectively to the thermodynamical temperature T and the detection effective temperature T_{eff} of the antenna, to ensure that the system is immune from unknown sources of spurious noise. *Known amplitude* means that there must be unambiguous correspondence between the output of the read out (measured in Volts) and the antenna excitation that produces it (measured in strain units, or amplitude of vibration, or energy change in the antenna). To this purpose, an absolute calibration of the antenna is needed. On all detectors this calibration is performed by applying pulses of known energy to the antenna by means of an auxiliary transducer and then reading out the response at the detector output. Calibration of the calibrator itself is a tricky step, but reliable procedures have been devised [15] to overcome this difficulty. On Explorer we have successfully tested a very different calibration: the antenna was excited by a near field a.c. gravitational force, generated by a spinning rotor driven at half the antenna frequency (so that its quadrupole moment would evolve at the antenna frequency). By moving the rotor at different distances from the antenna centre we were also able to make a significant check of Newton's $1/r^2$ law at distances 3 to 10 meters [16]. It is worth mentioning that on both antennas calibrations yielded a conversion factor (V^2 to K) corresponding, within a factor 1.5 or better, to what can be predicted by detector models, confirming that our understanding of these complex apparata is good.

With the detector so calibrated, we can check that the distribution of the so called *raw* , or unfiltered, data fits the Boltzmann statistics corresponding to the thermodynamical temperature: fig. 2 shows the energy distribution of one hour of data from Nautilus, well described by an exponential with a variance $T = 134mK$; this is, to our knowledge, the lowest temperature at which mechanical thermal noise has been observed.

The process of software filtering, close to a time derivative, looks for sudden variations in the antenna energy, against a slowly varying thermal backgound: it is filtering that allows us to reduce the noise level from 4.2 K to 10 mK and less. To filter the data, two strategies are used in parallel: the antenna signal is band pass filtered, with the use of lock-in amplifiers, around the two normal modes and then recorded at a rate of 3 Hz. The data are then filtered using a Wiener, time domain, optimum linear filter: as the phase information is lost in the lock-in, the squared output is proportional to the antenna *energy* change, and follows an exponential distribution. The second approach directly reads out the Squid output at higher frequency (220 Hz): by making use of aliasing, the band of interest is shifted down from 900 to about 20 Hz. A frequency domain matched filter (derived from the measured spectrum) is applied to this "fast" stream, producing an *amplitude* distribution proportional to the change in the antenna state of motion, and therefore following a Gaussian distribution.

Fig. 3 shows one typical, clean energy distribution for "slow data" at T_{eff}=7 mK and an amplitude distribution relative to Nautilus "fast data". The fitting curve is a Gaussian with a variance of 4 mK.

Obviously, any data point lying outside of the expected statistics is a candidate g.w. or, as we call it, an *event*. The second step in data analysis then consists of an exchange of event

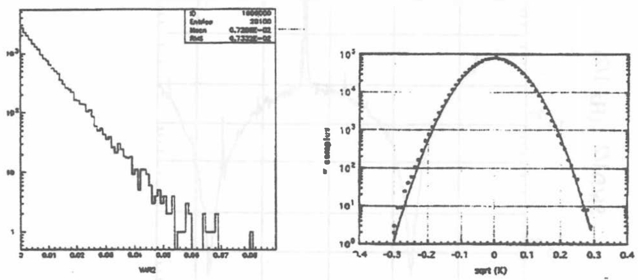

Figure 3: a) Energy distribution of filtered "slow" data, fitted by an exp. distribution $N(\Delta E) = N_0 exp(-\Delta E/k_B T_{eff})$ with $T_{eff} = 7mK$ and b)amplitude distribution of the output of the "fast' filter, fitted by a Gaussian law $N(x) = N_0 exp(-x^2/2\sigma^2)$ with a variance of 4.1 mK

lists between the various groups, looking for events that took place at the same time (time of flight of a g.w. between Frascati and LSU is about 20 ms). This is clearly a very delicate step, requiring great attention and numerous cross checks. Up to today, the most significant coincidence analysis has been done on six months of 1991 data from Allegro and Explorer [17]: in a search among all events exceeding 200 mK in both detectors, no coincidences were found in excess of the expected background of accidentals:

$$n_{coinc} = \frac{N_1 N_2}{N} \tag{12}$$

where N_1 and N_2 are the number of events recorded in the two detector out of the N total sampled data. Further results, regarding more recent data, should be released shortly.

Besides looking for bursts, resonant detectors can be employed in searches for stochastic background and for periodic signals emitted by pulsars: I will just recall that, as discussed in sect.2, a direct measure of $S_h(f)$ gives an upper limit on the stochastic g.w. background, and both Explorer and Nautilus have measured [18] spectral densities of $7 \cdot 10^{-22} Hz^{-1/2}$ on resonance, as shown in fig. 4, corresponding to a value of g.w. energy density equal to 500 times the closure value $\rho_c = 3c^2 H_0^2/8\pi G$. This is the first direct measurement of $\rho_{g.w.}$, although still orders of magnitude higher than constraints set by other observations, like nucleosynthesis [3].

Much better limits will be set by correlating two detectors operating at the same frequency [19]: it is estimated that two identical detectors (like, e.g. Nautilus and Auriga, assumed parallel and located at a distance smaller than the g.w. wavelength) if operated in coincidence for a time t_m of one year, would give

$$S_h(f_0) = \sqrt{\frac{S_{h1} S_{h2}}{\Delta f t_m}} \simeq 10^{-48} Hz^{-1} \tag{13}$$

that corresponds to a fraction $\Omega = 1.3 \cdot 10^{-3}$ of the closure density of the Universe. A new interest about measurements of g.w. stochastic background has recently arisen due to a theoretical model [20] based on string cosmology that predicts a g.w. spectrum with relevant components at frequencies about 1 kHz. Probably the best coincidence experiment, however, will be done between a resonant detector and an interferometer [19].

Finally, I will just mention the work, presently in progress [21], aiming at detecting monochromatic signals in our data: a little peak in the spectrum can be monitored for months, and its fluctuations in both frequency (a few mHz) and amplitude are compared to the changes we

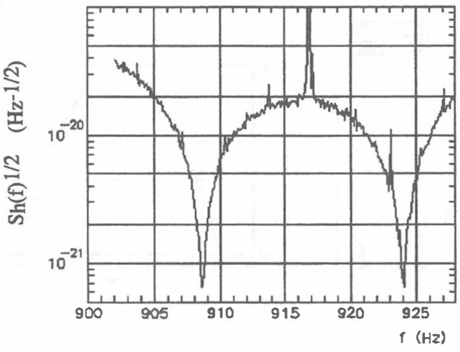

Figure 4: Strain spectral amplitude $[S_h(f)]^{1/2}$ measured by the Explorer antenna.

would expect due to Doppler effect (Earth rotation and revolution) and rotation of the antenna radiation pattern for some source position in the sky. Although we have no clear results so far, the challenging task of setting up both the spectral data base and the sky search procedure is now completed, and we can hope for interesting findings in the near future.

5 Perspectives for future detectors

5.1 Improving existing antennas

The read out of present antennas limit their sensitivity to $T_{eff} \sim 3 - 10mK$. A long way separates us from the quantum limit of linear amplifiers $T_{eff} \sim \hbar\omega \sim 10^{-7}K$ at 1 kHz, and work is being carried on in many labs to bridge this gap. Among the many efforts in this direction we recall [22]:

— A two mode inductive transducer, to achieve better coupling to the amplifier with two mechanical matching steps, under development at LSU

— A capacitive transducer with a very small gap (less than $10\mu m$) and double electrode, to increase the electromechanical coupling, has been made at Roma Tor Vergata and is ready to be implemented on an antenna

— A capacitive, a.c. biased transducer, capable to implement the so called Back Action Evasion non linear scheme, at Roma La Sapienza: it should allow, in principle, to improve sensitivity beyond the Standard Quantum Limit, that only applies to linear readouts.

— Improved SQUIDS, with energy sensitivity (measured in J/Hz) down to a few times the Planck constant *and* a good coupling to the input circuit; at L'Aquila, Twente (Holland), Maryland.

— Double SQUID cascade amplifiers, for more robust operation and for complete removal of any possible spurious pick-up along signal lines to room temperature, at Roma CNR and at Maryland.

— An improved microwave transducer, based on Sapphire technology, at UWA

— An optical transducer, based on a cryogenic Fabry Perot cavity, in collaboration between University of Maryland and Legnaro.

— Sophisticated adaptive matched software filters at Roma La Sapienza using a new, faster (5 kHz) acquisiton that will improve the event timing and amplitude accuracy.

All these are medium term, technologically challenging projects: if successful, they can each contribute, a small step at a time, to lower the limiting T_{eff} of future detectors down toward (and possibly beyond) the quantum limit. Vibration isolation will have to improve accordingly, or external noise (even at levels that are fully negligible today) will prevent us from taking advantage of the improved sensitivity.

5.2 Planning new antennas

As shown in eq. 1, the sensitivity of an antenna to a burst of g.w. is determined by $\Delta E_{min} = k_B T_{eff}$, as well as by the radiation pattern $f(\theta, \phi)$ and by the cross section

$$\Sigma = \frac{G}{c^3} M_a v_s^2 \alpha_n \tag{14}$$

where α_n is a numerical factor peculiar to the n-th mode of vibration. For the longitudinal modes of a thin cylindrical bar $\alpha_n = \frac{8}{\pi n^2}$ and $f(\theta, \phi) = sin^4\theta cos^4 2\phi$. It is obviously desirable to use a resonator with a larger mass, α_n factor and directivity pattern. All these things can be obtained at the same time by choosing a geometry that has more than one mode of vibration sensitive to g.w. (i.e. with a non negligible α_n). In the last couple of years the old idea of using a multimode detector has regained momentum: e.g. the five quadrupolar modes of a large ($\sim 3m$ in diameter) sphere would provide five independent detectors, each with a much larger mass and with different and complementary radiation pattern, adding up to a gain of $\sim$ 80 in cross section with respect to present bars. It now seems that, after a flourishing theoretical activity[23] experimental work on spherical prototypes might take off in the USA, Holland, Brazil and Italy. Another future detector, *the high frequency array* has been proposed in recent times [24]: the key point of that project is that, although one needs more massive antennas to increase the cross section, for no reason that mass must be confined in one single resonator. A detector with its mass distributed over many identical small oscillators would allow the experimenter to tune the resonance (by choosing the resonator dimensions) to any desired frequency, and in particular in the range 3-8 kHz where no other instrument (existing, in construction or even proposed) is sensitive. Besides, such an instrument, composed of many identical elements, would have a greater design flexibility and operating reliability, at the sole cost of a large engineering effort that would be needed to manage and operate, in an automatic and maintenance free fashion, an experiment whose output is provided by a large number (20-50) of elemental antennas.

The near future of resonant g.w. detectors appears very promising, with 5 detectors soon to operate simultaneously. The medium term future is also very challenging for the experimentalists, with these new, fourth generation detectors coming of age.

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References

1. J.Weber, *Phys. Rev.* **117**, 306 (1960).
2. For a good review of g.w. detectors and principles of operation see e.g. *The Detection of Gravitational Waves* D.G. Blair ed. (Cambridge Univ. Press 1991)
3. K.S. Thorne in *Three Hundred Years of Gravitation* S.W.Hawking and W.Israel eds. (Cambridge Univ. Press 1987)

4. P.F.Michelson, R.C.Taber *Phys. Rev.* D **29**, 2149 (1984).
5. P.Rapagnani *Nuovo Cimento* **5C**, 385 (1992).
6. H.J.Paik, *J.of Appl. Phys.* **47**, 1168 (1976) and N.Solomonson et al.*Rev. Sci. Instrum.* **65**, 174 (1993)
7. W.O.Hamilton et al. *Phys. Rev.* D **54**, 1264 (1996).
   See also http://phwave.phys.lsu.edu
8. P.Astone et al. *Phys. Rev.* D **47**, 362 (1993).
   See alsohttp://roma1.infn.it/rog
9. R.Leoni et al. *J.of Appl. Phys.* **68**, 4304 (1990).
10. P.Astone et al. "The gravitational wave detector Nautilus" submitted to *Astroparticle Physics*
11. P.Astone et al. *Europhys. Lett.* **16**, 231 (1991).
12. E.Coccia et al *Nucl. Instrum. Methods* **A355**, 624 (1995).
13. M.Cerdonio et al. *Phys. Rev.* D **50**, 4737 (1994).
    See also http://axln01.lnl.infn.it/
14. D.G.Blair et al. *Phys. Lett.* A **218**, 190 (1996).
    See also http://www.pd.uwa.edu.au/grav
15. S.Boughn et al.*Rev. Sci. Instrum.* **61**, 1 (1990)
16. Analysis and preliminary data can be found in P.Astone et al. *Z. Phys.* C **50**, 21 (1991); more recent results are in preparation.
17. P.Astone et al. in *Proc. of the 10th Italian Conference on General Relativity and Gravitational Physics* - M.Francaviglia ed. World Scientific 1994
18. P.Astone et al. *Phys. Lett.* B **385**, 421 (1996).
19. P.Astone et al. submitted to *Class. Quant. Grav*;
    M.Cerdonio et al. *Phys. Rev.* D **55**, 1741 (1997).
20. R.Brustein et al. *Phys. Lett.* B **361**, 45 (1995)
21. P.Astone et al. "An interactive method for the periodic sources search" *Proc. of the 1997 Aspen conference on Gravitational Waves.*
22. Details on most of the projects mentioned here can be found in the proceedings of two recent conferences on g.w. advances:
    -*First Edoardo Amaldi Conference on Gravitational Wave Experiments* - E.Coccia, G.Pizzella, F.Ronga eds., World Scientific 1995 and
    -*Virgo International Conference on G.W.: Sources and Detectors* - F.Fidecaro ed. World Scientific, 1997,
23. beside the many papers that can be found in ref. [22], we cite, without hope of completeness: W.W.Johnson, S.M.Merkowitz *Phys. Rev. Lett.* **70**, 2367 (1993) and *Phys. Rev.* D **51**, 2546 (1995).
    C.Z.Zhou et al. *Phys. Rev.* D **51**, 2517 (1995).
    J.A.Lobo et al. *Phys. Rev.* D **52**, 591 (1995), *Phys. Rev.* D **52**, 3735 (1995), *Europhys. Lett.* **35**, 253 (1996).
    E.Coccia et al. *Phys. Lett.* A **51**, 2517 (1995).
    G.Harry et al. *Phys. Rev.* D **54**, 2409 (1996).
24. M.Bassan et al. in *Proc. of the 11th Italian Conference on General Relativity and Gravitational Physics* - World Scientific, 1996