# Resonant Detectors for the Search of Gravitational Waves

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## Abstract

An overview of the experiments for the search of gravitational waves by means of resonant detectors is given. Since 1990 cryogenic resonant antennas have been in operation and data have been recorded by Explorer, Allegro, Niobe and Nautilus. The sensitivity for pulse detection with SNR=1 is now h $\approx$ 6 $10^{-19}$ (corresponding to a total energy of less than 0.001 solar masses for a source in the Galactic Center). The sensitivity for monochromatic waves is h $\approx$ 2 $10^{-25}$ for one year of integration and about 7 $10^{-22}/\sqrt{Hz}$ for a stochastic background detection.

Large resonant detectors operating at 1 kHz might reach, in a near future, a spectral amplitude sensitivity of the order of 7 $10^{-24}/\sqrt{Hz}$ and, for pulse and monochromatice wave sensitivity, respectively, h=3 $10^{-22}$ and h $\approx 10^{-27}$. Cross-correlating two of such large antennas for one year can give a sensitivity for stochastic background detection of the order of 3 $10^{-26}/\sqrt{Hz}$, corresponding to a ratio between the gw energy density to that needed for a close Universe of $10^{-6}$.

## 1. Resonant detectors

The gw detectors used by the groups of Legnaro, Louisiana, Perth and Rome are metallic cylindrical bars, with high mechanical quality factors. For capturing as more energy as possible from the gw the mass of the bar needs to be as large as possible. The Legnaro, LSU and Rome groups use aluminum bars L=3 m long, weighting about M=2300 kg with merit factors $Q > 10^6$. The Perth group uses a niobium bar (which has higher Q) resonating at 710 Hz and weighting 1.5 ton. When the bar is hit by a gw 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 gw.

It is possible to show (Astone, Pallottino, Pizzella 1996) that the minimum value of h that can be detected with SNR=1 is

$$h \approx \frac{1}{\tau_g} \sqrt{\frac{S_h}{2 \pi \Delta f}} \tag{1}$$

where $\Delta f$ is the detector bandwidth and $S_h$ here indicates the power spectrum of the noise referred to the antenna input. For a bar at the resonance frequency $f_o$ we have

$$S_h = \frac{\pi}{8} \frac{k T_e}{M Q L^2} \frac{1}{f_o^3} \tag{2}$$

where $T_e$ is the thermodynamic temperature plus a term due to the back-action from the amplifier, which, with a dc SQUID amplifier, is negligible.

The bandwidth of the resonant antennas is limited only by the transducer and by the noise of the electronic amplifier, because the resonant bar responds in the same way to the excitation due to the gw and to the brownian noise. It can be shown that the bandwidth is given by

$$\Delta f = \frac{f_o}{Q} \frac{4 T_e}{T_{eff}} \tag{3}$$

where $T_{eff}$ is the noise temperature for burst detection , that is $k T_{eff}$ is the minimum energy innovation that can be detected with SNR=1 after optimum filtering for very short signals.

Introducing Eqs. (3) and (2) in Eq. (1) we obtain

$$h \approx \frac{L}{\tau_g v^2} \sqrt{\frac{k T_{eff}}{M}} \tag{4}$$

where v is the sound velocity in the bar material (v=5400 m/s in aluminum)

With M=2300 kg, L=3 m, $\tau_g$=1 ms, in order to observe a gw due to a SN at the Galactic Center (optimistically h=3 $10^{-18}$) we need $T_{eff} = 0.2$ K. If the same gw comes from the Virgo Cluster we need $T_{eff} = 1.4 \ 10^{-7}$ K.

It is interesting to compute the bandwidth for the target sensitivity. From Eq.(3), with $T_{eff} = 1.4 \ 10^{-7}$ K, T=0.1 K and Q=1 $10^7$, we find $\Delta f \approx 300$ Hz. This compares favorably with the interferometers bandwidth.

For the detection of monochromatic waves the sensitivity is given by (Astone, Pallottino, Pizzella 1996)

$$h = \sqrt{\frac{2\,S_h(f)}{t_m}} = \sqrt{\frac{\pi\,k\,T_e}{M\,Q\,v^2\,f_o\,t_m}} \qquad (5)$$

where h is the amplitude of the wave that can be detected with SNR=1 and $t_m$ is the length of the time of measurement. The first equality is valid at any frequency, the second one only at the resonance.

A resonant detector can also measure the gw stochastic background. The relationship between the gw density ratio $\Omega$ and the power spectrum $S_h$ is

$$\Omega = \frac{4\,\pi^2}{3}\,\frac{f^3}{H^2}\,S_h(f) \qquad (6)$$

where H is the Hubble constant.

In addition to the bars new projects for resonant detectors begin to be on the air. Most of the groups considered above (as well as two other groups, one in Brazil and the other one in Holland) are considering the possibility to start new experiments with resonant antennas. The idea is to use spherical detectors that have, basically, two advantages with respect to the other 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) the spherical detector is sensitive to gw coming from all directions and with any degree of polarization.

In fact, one sphere is equivalent to 5 bars properly oriented on the Earth surface, each one with a mass 3/4 of the mass of the sphere (Coccia 1994). Estimations of the sensitivity for a 3 m sphere resonating at 1000 Hz and cooled at 20 mK, give, for 1 ms bursts, $h \approx 3 \cdot 10^{-22}$. The spectral amplitude sensitivity would be $7 \cdot 10^{-24}/\sqrt{\text{Hz}}$ and the sensitivity for monochromatic waves should approach $h \approx 10^{-27}$.

## 2. Operation of the resonant detectors and preliminary results

The resonant bars (Astone et al 1993, Blair et al 1994, Geng et al 1994) were the only detectors in continuos operation since 1990. They have reached a burst sensitivity, with SNR = 1, of the order of $h \approx 6 \cdot 10^{-19}$ and a spectral amplitude sensitivity of less than $1 \cdot 10^{-21}/\sqrt{\text{Hz}}$. In one year of continuous operation, with such a spectral amplitude sensitivity, they can detect monochromatic waves with amplitude of $h \approx 2 \cdot 10^{-25}$ (Astone 1996).

Coincidences experiments were performed between ALLEGRO and EXPLORER. No gw events were found during a period of 122 days in 1991 with amplitude greater than $h \approx 4 \cdot 10^{-18}$. Coincidences were also searched in the period day 180 to day 280 of 1995 between the antenna EXPLORER and the antenna NIOBE. A coincidence excess was found of about a dozen events over the 100 days. To confirm this last result, however, additional data analysis is required and work is in progress.

More recently two ultracryogenic resonant antennas are entering in operation. NAUTILUS (Astone et al 1994) in Frascati (Rome) and AURIGA (Cerdonio et al 1994) at

Legnaro (Padua). These two antennas will operate in coincidence for the search of gw bursts and for the measurement of the stochastic background.

In Tokyo (Suzuki et al 1994) a resonant antenna of a particular shape has been realized, resonating at about 60 Hz, that can detect gw possibly emitted by the Crab pulsar. The sensitivity so far reached is h>2 $10^{-22}$, whilst the optimistic expected value is of the order of $10^{-24}$.

| **Table I** | start | main characteristics | present sensitivity | | target sensitivity | | | |
|---|---|---|---|---|---|---|---|---|
| | | | $\Delta f$ Hz | sensitivity for 1 ms bursts | $\Delta f$ Hz | sensitivity for 1 ms bursts | spectral amplitude 1/√Hz | $\Omega$min |
| ALLEGRO USA | 1970 (1991) | M=2300 kg T=4 K | 1 | 6 $10^{-19}$ | 50 | 1 $10^{-20}$ | 7 $10^{-22}$ | |
| AURIGA Legnaro | 1989 | M=2300 kg T=0.1 K | | | 50 | 3 $10^{-21}$ | 7 $10^{-23}$ | 4 $10^{-5}$ 920 Hz |
| EXPLORER Roma | 1971 (1990) | M=2300 kg T=2 K | 1 | 6 $10^{-19}$ | 50 | 1 $10^{-20}$ | 7 $10^{-22}$ | |
| GRAIL Holland | 1994 | M=15 ton T=0.02 K | | | 50 | 6 $10^{-22}$ omni directional | 1 $10^{-23}$ | 2 $10^{-6}$ 1 kHz |
| NAUTILUS Frascati | 1986 (1995) | M=2300 kg T=0.1 K | 1 | 6 $10^{-19}$ | 50 | 3 $10^{-21}$ | 7 $10^{-23}$ | 4 $10^{-5}$ 920 Hz |
| NIOBE Australia | 1978 (1993) | M=1500 kg T=6 K | 1 | 6 $10^{-19}$ | 50 | 1 $10^{-20}$ | 7 $10^{-22}$ | |
| TOKYO (CRAB) | 1975 (1991) | M=1200 kg T=4.2 K | $10^{-4}$ | 2 $10^{-22}$ continuous h | $10^{-4}$ | 2 $10^{-24}$ continuous h | | |
| GRAIL OMEGA TIGA | R&D now | M=40 ton T=0.02 K | | | 50 | 3 $10^{-22}$ omni directional | 7 $10^{-24}$ | 1 $10^{-6}$ 1 kHz |

In Table I we indicate the present and expected sensitivity for various antennas. The burst sensitivity can be made larger than the one available now by improving the electromechanical transducers, that is by increasing the bandwidth. Note that a new group in Holland is beginning a gw experiment with a resonant spherical detector.

In the start column we have indicated the time when the experiment actually started to be designed and, in parenthesis, when it started, although with a sensitivity not yet the target one, to produce new data.

The last column indicates the minimum gw density ratio $\Omega$ (with respect to the critical density) that can be determined with two equal near detectors operating continuously for one year using Eq. (5) and having considered H=100 km s$^{-1}$ Mpc$^{-1}$.

Finally in the last row we have reported the expected performances of the experiments with spherical detectors that are being planned. The target sensitivity for all resonant detectors has been evaluated assuming that wide band transducers become available in the near future (Bassan, Pizzella 1996).
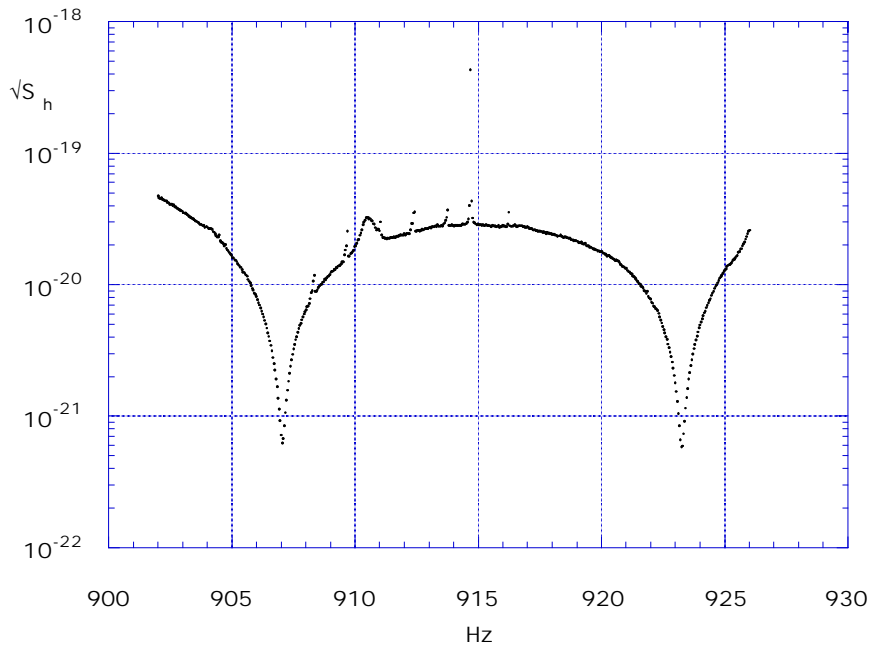


**Fig. 1 –** Sensitivity to stochastic gw background with SNR=1 for EXPLORER. T=2.4 K, M=2300 kg, Q=5 10$^6$, average spectrum over 36 hours (1994).

For the experiments already performed we show in Fig. 1 the experimental spectral amplitude noise of Explorer reported at the detectors input. We notice the value of 7 10$^{-22}$/$\sqrt{\text{Hz}}$ at the two resonances of the detector.

From the data shown in the figure, one can deduce even with one single detector an upper limit for the stochastic gravitational waves background in the Universe, although with a poor sensitivity. It is found (Astone et al 1996) $\Omega \leq 300$.

## 3. Conclusions

We remark that, in order to reach the target sensitivity, further development of the present techniques is needed. Since it is not possible to guess up to what extent a technique can be implemented, it remains very difficult to foresee the time when the above detectors will be so sensitive to observe gravitational collapses occurring at the Virgo cluster distances.

As far as the comparison with the interferometric antennas, it is our opinion that the two techniques implement each other, the interferometers being more suited for frequencies below 1 kHz, the resonant detectors being more sensitive at 1 kHz and above.

It is important however, in conclusion, to realize that there are, at present, sensitive resonant antennas in operation, with a duty cycle that is of the order of 50 %, and that they are taking data in an unexplored field of physics.

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