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Detection of gravitational waves with resonant antennas

Francesco Ronga

INFN Laboratori Nazionali di Frascati via E. Fermi Casella Postale 13 I 00044 Frascati Italy

E-mail: `Francesco.Ronga@lnf.infn.it`

Abstract. The status of the 4 operating cylindrical gravitational waves resonant antenna detectors is summarized. A short review is given of the experimental results and of the next generation projects. Resonant detectors are now sensitive to the strongest potential sources of gravitational waves in our galaxy and in the local group. Recently interferometric detectors have achieved very good perfomances, but resonant detectors are still competitive particularly for what concern the very good live-time.

1. Introduction

Gravitational waves are predicted by the Einstein's General Relativity. Indirect evidence for gravitational waves was established after the discovery by Hulse and Taylor[1] of the binary pulsar system PSR 1913+16. The rate of change of the orbital period of this system is in good agreement with the one predicted by the General Relativity due to the gravitational wave emission. The direct detection of gravitational waves and the study of the distinguishing characteristic of such waves, i.e. propagation speed, polarization states and multipolar structure will provide one of the most fundamental test of the general relativity. The detection of the gravitational wave will also open a new opportunity for astronomy: in fact the universe is transparent to gravitational waves. The electromagnetic radiations normally does not escape from compact objects and is absorbed by the interstellar dust. Gravitational wave and neutrino astronomy will increase the amount of observable universe, because they will investigate places that are completely inaccessible to the electromagnetic radiation and probably will change our knowledge of the universe evolution.

The experimental search for gravitational waves was initiated by Joseph Weber in the early 60. His detector was very similar to the modern cylindrical resonant bar detectors. The main difference is in the operating temperature (now detectors are kept at very low temperature to reduce the thermal noise) and in the conversion of the mechanical vibration signal into an electrical signal. There was a great excitement following the Weber announcement in 1969 of simultaneous signals in two detectors [2] one near Washington DC, the other one in Chicago. This excitement produced the birth of many research groups around the world and the expansion of the experimental search of gravitational waves. Weber's observation were not confirmed even with new more sensitive detectors. However the importance of Weber as pioneer should not be forgotten. He was also one of the first to propose interferometers as gravitational wave detectors. The current resonant bar detectors have an energy sensitivity 4-5 order of magnitude larger than the original Weber device and they are sensitive to the strongest potential sources of gravitational waves in our Galaxy and in the local group.

2. Gravitational waves and resonant detectors

In Einsteins gravitational theory the gravitational wave field is described by deformation in the space-time geometry using the metric tensor g_{ik}:

$$g_{ik} = g^0_{ik} + h_{ik} \tag{1}$$

where h_{ik} is the gravitational wave perturbation tensor having components much smaller than the unity. It can be shown that for a plane wave propagating in the x direction the only non zero components are:

$$h_{yz} = h_{zy} = h_{\times} \qquad h_{yy} = -h_{zz} = h_{+} \tag{2}$$

So in general in order to fully reconstruct a gravitational wave 4 independent quantities should be measured by detectors : the two polarizations h_x and h_+ and two angles that define the source direction. In theories different from general relativity a scalar field could be also present. The running detectors (cylinders and interferometers) measure only one quantity that is a combination of the 4(5) quantities describing the gravitational wave; the full reconstruction of gravitational waves can be done only combining the measurements of several detectors. Only a spherical detectors, having five degenerate quadrupolar oscillations mode ,can produce 5 independent measurements that can allow the full reconstruction of a gravitational wave with only one detector[3].

Gravitational waves are generated by the acceleration of masses with quadrupolar distributions. There is a very simple upper limit for the amplitude of the gravitational waves:

$$h \ll \frac{1}{c^4}(\frac{GM}{r})(\frac{GM}{R}) \tag{3}$$

where M is the mass, r is the distance and R is the radius of the astrophysical object. The numbers obtained using this formula are very small, for example for a neutron star having 1 solar mass and R=10Km and at at a distance of 10 Mparsec $h \ll 10^{-21}$. The energy flux of a gravitational wave is given by:

$$F = \frac{c^3}{16G\pi}\frac{d}{dt}(h^2_{\times} + h^2_{+}) \tag{4}$$

For a wave having $h = 10^{-21}$ and frequency 1 kHz the energy flux is about $0.3 watt/m^2$. This very large energy flux, comparable to the flux of the Moon light on the Earth is difficult to detect due to the very small absorption cross section of matter.

The frequency of emission of gravitational waves is related to the astrophysical object mass and dimension; as order of magnitude $\nu \ll \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}}$. The current resonant antennas are sensitive in the kHz range and therefore the most likely sources to be detected are sources of small dimensions and very fast moving: supernova remnants, coalescence of compact binaries, fast rotating pulsars ecc.[4][5].

A cylindrical bar detector of mass M, length L subject to a gravitational wave is equivalent to an oscillator of the same resonant frequency ν_o having two masses each of value M/4 connected by a spring of length $l = 4L/\pi^2$ and subject to a driving force $\ddot{h}l/2$. Using this simple equivalence many useful numerical relations can be evaluated. For example for 1 msec burst of $h = 10^{-20}$ the absorbed energy in the bar is $E = 10^{-29}$ Joules and the vibration amplitude is $\xi = 10^{-20}$ meters. So, in order to detect useful astrophysical signals, detectors should be able to measure very tiny amount of energy: this is the main difficulty of this search. Physics results are often shown in function of the strength of a burst (modeled as a pure Dirac δ-function) quantified by its Fourier amplitude H_o, which is related to the energy E_s deposited in the bar by:

$$H_0 = \frac{1}{4L\nu_o^2}\sqrt{\frac{E_s}{M}} \tag{5}$$

An important parameter to be considered is the Q of the oscillator: for example in the burst searches high Q means a longer time in an excited state of the bar and therefore improvement in the signal to noise ratio.

The mechanical energy is converted in an electrical signal using a scheme like the one reported in figure (1). At the end of the cylinder there is an electromechanical transducer, consisting of a charged capacitor with two parallel plates, one of which moves with respect to the bar. The motion of the wall changes the capacitanche of the transducer and therefore produces an electrical signal amplified with a very sensitive amplifier, usually a SQUID, with a transformer in order to have impedance matching. The transducer has a resonant frequency very close to the one of the bar. The system can be modeled as two coupled mechanical oscillators: bar and transducer. This system produces an amplification of the mechanical signals that is proportional to $\sqrt{\frac{M}{m}}$ where m is the transducer's mass. Another effect is the splitting of the main resonant mode of the bar in two near modes. The electric circuit is another oscillator; so the entire detector, antenna transducer and electrical circuit, can be modeled as a system of three coupled oscillators.

The main noises in this scheme are those due to the Brownian motion of the bar and of the transducer (the thermal noise) and the noise of the amplifier. The first one can be reduced going to very low temperature. The first cryogenic detector was operated at the beginning of the 1980s by the Fairbank group in Stanford, followed by the detector EXPLORER(INFN) placed at CERN and by the LSU group detector ALLEGRO. Only at the beginning of the 1990s, however, did cryogenic detectors began continuous operational mode and hence the role of reliable instruments of physics.

Another important quantity is the energy conversion coefficient that can be increased by decreasing the gap and increasing the electric field of the transducer. Gaps of the order of 10μ and electrical fields up to 100KV/meter are now currently used.

The data are usually filtered with an adaptive filter matched to delta-like signals for the detection of short bursts . This search for bursts is suitable for any transient gravitational wave which shows a nearly flat Fourier spectrum in the sensitivity bandwidth of each detector.

3. Status of resonant bar detectors

In the last few years an important improvement has been achieved by detectors of this kind: the bandwidth has been enlarged from a typical 1 Hz value to almost 100 Hz[6],[7]. This evolution is shown in figure (2). Before 2001 the best spectral strain sensitivity was concentrated in less than one Hz around the two resonant frequencies (figure 2 top). But it is important to remember that this was due not to an intrinsic limitation of the device (the resonant bar) but to the need of signals larger than the electrical noise. In 2001 a new transducer and a new SQUID amplifier were mounted in the EXPLORER antenna and for the first time in the world was possible to have a bandwidth of a few tens of Hz. Now the record belongs to the AURIGA antenna having a strain sensitivity $S_{hh}^{1/2} \leq 10^{-20}$ in a band of about 110 Hz (figure 2 bottom).

An important parameter to consider in the coincidence search is the resolution time for burst. The resolution time is inversely proportional to the bandwidth. In EXPLORER and NAUTILUS the resolution time has been measured using cosmic rays shower detected by counters on the top and on the bottom. The σ is of the order of 2 msec.

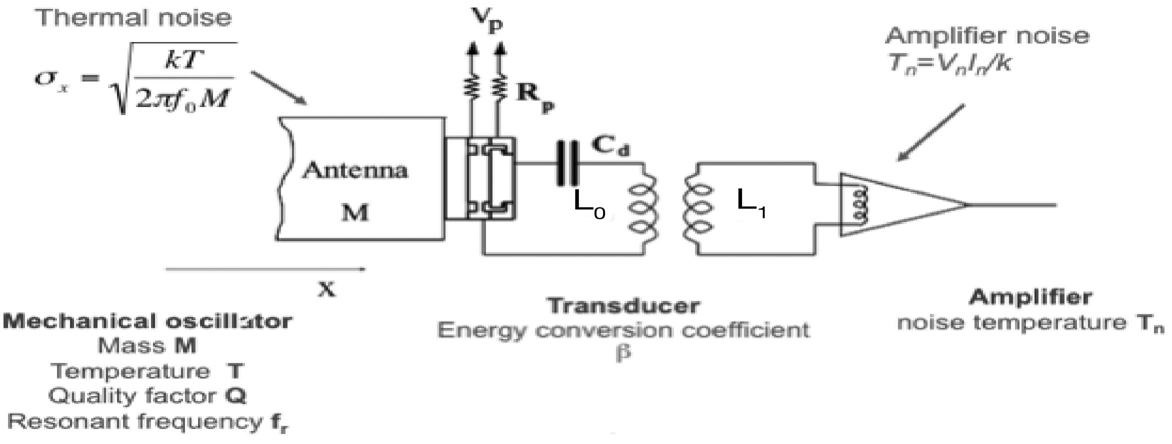

Figure 1. Resonant bar antenna, transducer and electrical circuit.

Four cylindrical bar detectors are currently operating: ALLEGRO (Lousiana State University,USA), AURIGA(Legnaro, ITALY), EXPLORER(CERN), NAUTILUS(Frascati,Italy). The main characteristics are reported in table 1. The EXPLORER and NAUTILUS antennas are operated by the same group (ROG). The four antennas are oriented almost parallel (see table). This allows a combined search of gravitational waves produced in bursts. An international collaboration(IGEC) has been formed and the results for years 1997-2000 are published in [8]. The observations of this IGEC search are consistent with no detection of gravitational wave burst events. An upper limit has been set on the rate of gravitational wave bursts with Fourier component $H > 10^{-20} Hz^{-1}$ The upper limit is flat at high search thresholds, $H > 10^{-20} Hz^{-1}$ and is of the order of 1 event per year. It is important to note that this upper limit for high search threshold is almost two order of magnitude lower than the one due to LIGO[10]. In the period of time january 2001 - june 2003 only EXPLORER and NAUTILUS were running, so the IGEC collaboration was in stand-by. IGEC has resumed again in june 2003 when other antennas became ready to take data. This new IGEC analysis should improve the sensibility in H by a factor 2.

In 2002 the ROG collaboration presented the results of a search for GW bursts with the EXPLORER and NAUTILUS cryogenic bar detectors operating for nine months in the year 2001 [9]. The EXPLORER-NAUTILUS 2001 search had several important features: both detectors were operating at an unprecedented sensitivity and sidereal time analysis was performed in order to look for specific galactic signatures. A small excess of events with respect to the expected background was found, concentrated around sidereal hour four. At this sidereal hour the two bars are oriented perpendicularly to the galactic plane, and therefore their sensitivity for galactic sources of GW is maximal.

After an upgrade of the detectors, new data of EXPLORER and NAUTILUS are now available from the 2003 run. The results of the new data analysis is shown in figure (3) together with the IGEC1 and the LIGO results.

In figure (3) the comparison of the search sensitivity with the interferometers is done using the quantity h_{rss} (the root sum square of h) and a gaussian waveform $h(t) = h_{rss}\frac{2}{\pi\tau^2}e^{\frac{-t^2}{\tau^2}}$ with $\tau = 0.1 msec$. The orientation considered was the optimal one. The interpretation of the EXPLORER-NAUTILUS result of the 2001 run [9] in term of a possible continuous and uniform (in time) arrival of burst signals at h_{rss} level of the order of 1.8×10^{-19} is excluded by this result at 95% confidence level. However, some clustering of coincidences during short periods of time is present in these data, a feature already noted in past runs.

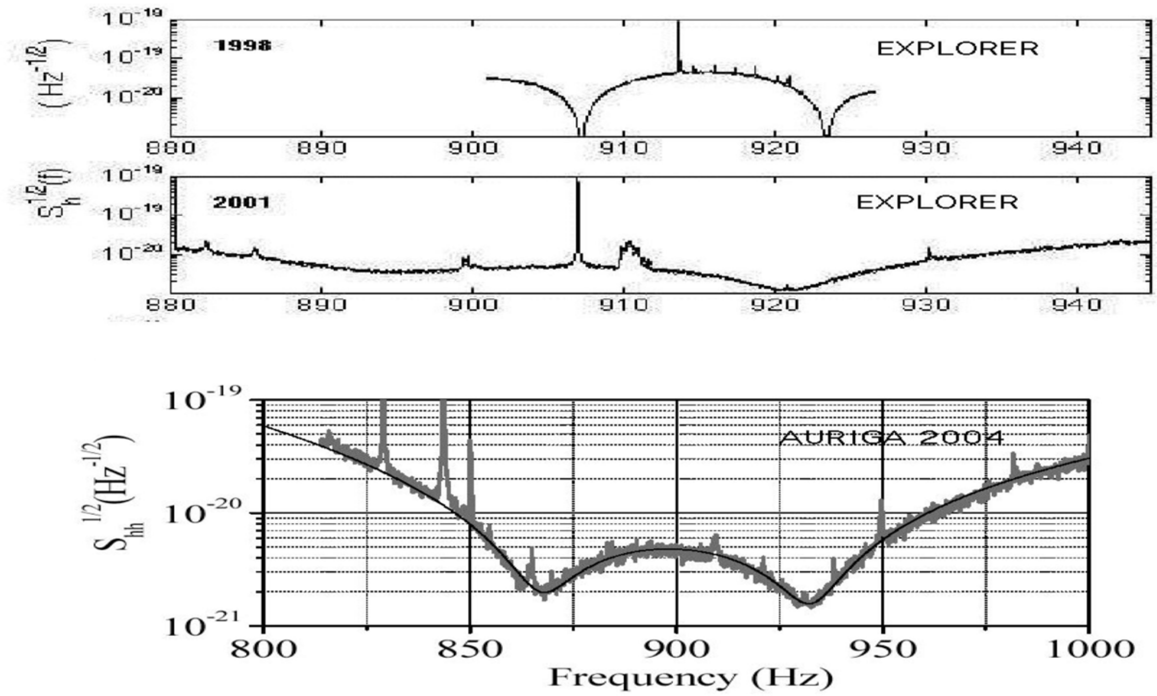

Figure 2. The spectral sensitivity of Explorer (top) in 1998 before the improvements in the trasducer and in the amplifier and in 2001(center) after the improvements and the AURIGA antenna (bottom) in 2004

Table 1. Summary of detector characteristics. The reported misalignment is the angle between the bar axis and a common direction.

Detector	ALLEGRO	AURIGA	EXPLORER	NAUTILUS
Material	Al5056	Al5056	Al5056	Al5056
Mass [kg]	2296	2230	2270	2260
Length [m]	3.0	2.9	3.0	3.0
Interval with $S_{hh}^{1/2} \leq 10^{-20}$ [Hz]	907	850	885	918
	925	960	930	955
Temperature [K]	4.2	4.5	2.6	2.5
Longitude	268°50'E	11°56'54"E	6°12'E	12°40'21"E
Latitude	30°27'N	45°21'12"N	46°27'N	41°49'26"N
Azimuth	−40°E	44°E	39°E	44°E
Misalignment [deg]	9	4	2	3

There is no space here to discuss all the other results obtained by the resonant bar detectors. However, it is important to note that continuous data taking is a very important issue in search for episodical sources as, for example, gamma ray burst[11] , giant flares[12] etc.

4. Future projects

In the last two years the improvements in the interferometer performances, particularly LIGO and VIRGO, have been impressive. At 1 khz LIGO has $S_{hh}^{1/2}$ a factor almost 10 better than the

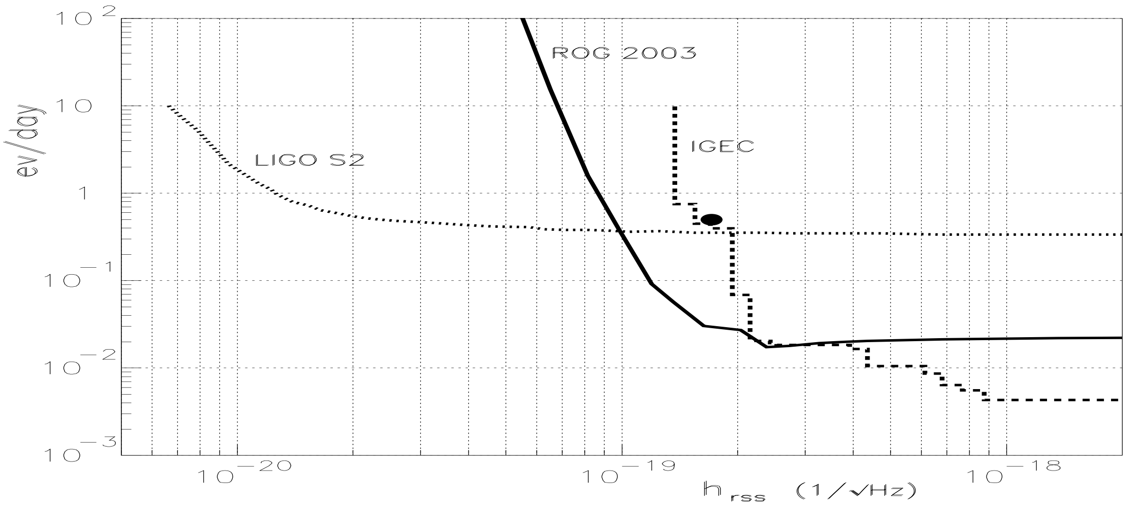

Figure 3. Upper limit (at 95 %) on the rate of events arriving on Earth as a function of h_{rss}, assuming gaussian-shaped bursts with $\tau = 0.1$ ms. The LIGO and IGEC curves are from fig.14 of ref.[10]. The large point represents roughly what could have been the rate deduced the EXPLORER-NAUTILUS 2001 results.

best resonant antenna AURIGA. So, is important to discuss the future prospects to assess if in the future there is still space for this kind of device. Important advantages of the resonant detectors are: the construction cost (a few percent of the construction cost of one interferometer) and the ease of operation (data taking is without people in shift for most of the time). Moreover there is still room for a large improvement in sensitivity. The final sensitivity of this kind of detector is dominated by the quantum noise. The quantum limit of 1 kHz bar (without considering the transducer) is $\Delta E_{min} = \hbar\omega_0 \approx 6 \times 10^{-31}$ Joules. For a bandwidth of 300 Hz this corresponds to $S_{hh}^{1/2} \approx 5 \times 10^{-23} Hz^{-1/2}$ better than LIGO /VIRGO at 1 KHz.

Another limitation comes from cosmic rays. Cosmic rays are currently detected in EXPLORER and NAUTILUS and used to check the detector performances. The rate is low because the current bar detectors are sensitive only to events leaving in bar a large amount of energy : i.e., big cosmic ray extensive air showers or muons/hadrons interacting in the bar. At the quantum limit sensitivity the rate will be much higher and should be of the order of 5000 events/day in an aluminum bar. This number has a large uncertainty and there are hints that effects due to superconductivity could increase the amplitude of the detected signals[13]. The only way to reduce cosmic rays is to go underground. A moderate depth may be enough. The particle excitation of a bar is studied in a dedicated experiment using a particle beam[14].

The next step to improve the sensitivity will be to cool the bars at 0.1 Kelvin. This was done in the past for AURIGA and NAUTILUS but is not done yet with the new transducers and amplifier chains. For example after this step AURIGA should go to a mimimun $S_{hh}^{1/2} \approx 2 \times 10^{-22}$ (a factor ≈ 3 worse than LIGO/VIRGO and a bandwith with $S_{hh}^{1/2} \leq \times 10^{-20}$ much bigger than 200 Hz. Improvements in the transducers and in the electronic amplifiers are expected in the future. The increase of performances of those devices in the last few years has been impressive. For example the noise of the SQUID chain developed by the AURIGA group was 2000 $\hbar$ in 1998 and is today 25 $\hbar$ [15]. There are also other approaches in the transducer-amplifier chain using radio-frequency or optical cavities. It is interesting to note that at radio-frequency there are commercial amplifiers already achieving the quantum limit[16].

Another way to improve the sensitivity is the increase of detector masses or the change of the shape. There is a dedicated talk at this conference on spherical detectors[17]. The MINIGRAIL spherical detector having f=2.9 KHz and mass=1400 Kg is now in the commissioning stage in Leiden. Another spherical detector having the same mass is in construction in Brasil. There is also a proposal, called SFERA, with groups from Switzerland, Italy and Netherlands to build a 2 meters CuAl 6% spherical detector of 33 tons mass. This detector will have as best sensitivity $S_{hh}^{1/2} \approx 2 \times 10^{-22}$ and $S_{hh}^{1/2} \leq \times 10^{-20}$ in the range 820-1350 Hz, using today technology for transducers and amplifiers . At the quantum limit the best sensitivity will be about a factor 10 better. A big advantage of a sphere is due to the isotropy: isotropy allows a gain of a factor 1.9 (in amplitude) with respect to a cylinder or an interferometer. Another advantage is the measurement of all the components of the gravitational wave tensors with the same detector.

Another interesting proposed detector is a dual torus detector (DUAL) [18]. At the quantum limit a DUAL molybdenum detector of a 16.4 Tons , equipped with a wide area selective readout, would reach a spectral strain sensitivity $2 \times 10^{-23} Hz^{-1/2}$ between 2-6 kHz, much lower than VIRGO/ LIGO. A 62.2 tons version with silicon carbide (SiC) ceramic matrix has been also proposed. In this case the sensitivities will be less than $1 \times 10^{-23} Hz^{-1/2}$. The DUAL detector involves many new ideas and technologies. An R&D program has started to demonstrate the feasibility of such detector.

5. Conclusions

The near future will be very exciting for this field. With the improvements in the detector sensitivities, there are non zero chances to have the direct detection of gravitational waves and to start gravitational wave astronomy. However, due to the noise, a network of detectors is necessary to operate in coincidence. Resonant bar detectors, having a very high duty cycle will be very important for multi-detector coincidences search and to look to episodical sources. An international collaboration is necessary to coordinate the operations of all the detectors around the world. Even if the sensitivity of the current resonant detectors is lower than that of LIGO/VIRGO there is room for improvements to be competitive, at low cost, with the interferometers, particularly at high frequencies.

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