INSTITUTE OF PHYSICS PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **21** (2004) S377–S383 PII: S0264-9381(04)70669-3

Resonant-mass detectors: status and perspectives

Viviana Fafone

INFN, Frascati National Laboratories, Via E Fermi 40, 00044 Frascati (Rome), Italy

E-mail: viviana.fafone@lnf.infn.it

Received 20 October 2003
Published 3 February 2004
Online at stacks.iop.org/CQG/21/S377 (DOI: 10.1088/0264-9381/21/5/001)

Abstract

We review the main features and the perspectives of the resonant-mass gravitational wave detectors. Bar detectors have been taking data for the last few years with burst sensitivity $h \simeq 4 \times 10^{-19}$ at SNR = 1, or, in spectral units, 3×10^{-22} Hz$^{-1/2}$ over a bandwidth of about 1 Hz, with a duty cycle mainly limited by cryogenic operations. In addition to the systematic search for impulsive events, the data collected are being used to detect periodic waves over long time periods, to give new upper limits for the stochastic background of cosmological origin, and to study possible correlation with gamma ray bursts. The recent developments of readout electronics have allowed us to increase the detection bandwidth to a few tens of Hz, and even larger bandwidths are expected in the near future. Resonant-mass detectors of spherical shape have been investigated and many different solutions have been proposed. Two small (about 60 cm in diameter) spheres are under construction in Holland and Brazil. Recently, a new scheme has been proposed, the 'dual' detector, which can provide a wideband performance. We briefly describe the status of traditional resonant-mass detectors and the main features and the state of the art of the advanced acoustic detectors.

PACS number: 04.80.Nn

1. Introduction

The experimental search for gravitational waves (GWs) was started by Joseph Weber in the early 1960s, at a time when very little was known about their possible sources. He developed the first resonant-mass detector, made of a massive bar with a fundamental longitudinal frequency of about 1.6 kHz and a motion sensor converting the vibrations of the bar into an electric signal. His efforts stimulated the birth of new generations of resonant detectors, involving the use of cryogenic and superconducting techniques for noise reduction and the development of new detectors based on laser interferometry between widely spaced bodies.

The first cryogenic resonant-mass detector that achieved long-term operation was EXPLORER [1] at CERN, followed by the LSU group detector ALLEGRO [2] and by NIOBE [3] at UWA. In the years 1982–1984 a feasibility study was conducted to establish the technical possibility of cooling a multiton Al 5056 bar to milliKelvin temperatures [4]. In 1995 and in 1997, respectively, the ultracryogenic detectors NAUTILUS [5], located at the INFN Frascati Laboratories, and AURIGA [6], located at the INFN Legnaro Laboratories, started taking data.

The principle of operation of resonant-mass detectors is based on the assumption that any vibrational mode of a resonant body that has a mass quadrupole moment, such as the fundamental longitudinal mode of a cylindrical bar, can be excited by a GW with nonzero energy spectral density at the mode eigenfrequency.

The mechanical oscillation induced in the antenna (made of a high Q material, at least of the order of 10^6) by interaction with the GW, is transformed into an electrical signal by a motion or strain transducer and then amplified by an electrical amplifier. The sensitivity of the detector is limited by three sources of noise which, referred to the output are: the narrowband thermal noise, as the input wideband stochastic dissipative force, due to the internal friction in the resonant mass, appears at the output after passing through the mechanical transfer function of the system; the wideband amplifier noise, which appears directly at the output and the narrowband back-action noise, originated from the back-energy flow from the amplifier, which excites the resonant mass. The useful bandwidth of such detectors is by no means limited to the very narrow width of the high Q mechanical resonance. Rather, it is the amplifier noise that limits the bandwidth. The lowest spectral noise is found in the frequency region where the narrowband (thermal plus back action) noises dominate the amplifier noise, and there the noise level is the sum of the two. As a consequence, any reduction in the amplifier noise and/or increase in coupling, increases the antenna bandwidth.

2. Status of bar detectors

During these years, experimentalists have devoted continuous effort to improve the antenna sensitivity. All the upgrades are mainly devoted to:

- increasing the duty cycle and lowering the background noise, by upgrading the cryogenics to minimize maintenance stops and to ensure more stable operating temperature, and by acting on the vibration attenuation system, including the thermal links between refrigerating stages and the electromechanical sensitive components. The goal is to reach a performance in duty cycle and low background like that obtained by ALLEGRO in the period 1997–2000, when it collected an effective observation time higher than 90% [7].
- improving the sensitivity and the useful bandwidth, by acting on the readout components. These efforts promise to be successful, as recently shown by EXPLORER and NAUTILUS where upgraded transducers, more strongly coupled to the bar, and less noisy single-stage SQUID amplifiers have been used. Even better results are expected very soon from ALLEGRO and AURIGA which will also make use of double-stage SQUID amplifiers with an energy resolution of less than 100 quanta and (in the case of AURIGA) of a high Q superconducting LC coupling circuit resonating at the bar frequency. Also the ROG collaboration is developing a double-stage readout system to be installed on EXPLORER and NAUTILUS.

The status of the bar detectors is at present as follows.

- ALLEGRO has continuously taken data until March 2000 with a sensitivity to GW bursts $h \simeq 9 \times 10^{-19}$, corresponding to a noise temperature after filtering $T_{\rm eff} \simeq 10$ mK ($T_{\rm eff}$ describes, in kelvin, the minimum detectable energy innovation). It was relocated in 2000. After a run during the LIGO E7, the system was upgraded. An old inductive transducer developed at Maryland University was adapted and installed, coupled to a commercial single-stage dc SQUID. All these improvements resulted in a higher coupling. The new setup was tested during the LIGO S2 run. About one month of data were collected, for three different orientations of the bar (parallel to the IGEC detectors, parallel to the LLO y-axis and to the LLO x-axis). A new run is planned in coincidence with the LIGO S3. In 2004 a further upgrade of the readout chain is planned with a new two-mode transducer developed in collaboration with the University of Maryland, coupled to a double-stage dc SQUID (AURIGA design). The new system will have a bandwidth of about 60 Hz, at the level $\tilde{h} \simeq 1 \times 10^{-21}\,{\rm Hz}^{-1/2}$ around 900 Hz (the typical resonance frequency of present bar detectors). Details are given in [8].
- AURIGA took data until August 1999, with $\tilde{h} \simeq 4 \times 10^{-22}\,{\rm Hz}^{-1/2}$, over 2 Hz (that is, for bursts, $h \simeq 2.5 \times 10^{-19}$ and $T_{\rm eff} \simeq 1$ mK). A new readout (a new capacitive transducer read by a double SQUID amplifier and with the LC coupling circuit tuned to the mechanical modes of the detector) and new mechanical suspensions (with an attenuation of 360 dB at 1 kHz) have been developed. The system will be operative in the year 2004. The expected strain noise is (phase I, at $T = 1.5$ K): $\tilde{h} \simeq 6 \times 10^{-22}\,{\rm Hz}^{-1/2}$ at the resonances, and $\tilde{h} \leqslant 10^{-21}\,{\rm Hz}^{-1/2}$ over 40 Hz; after one year (phase II, at $T = 100$ mK): $\tilde{h} \simeq 2 \times 10^{-22}\,{\rm Hz}^{-1/2}$ at the resonances, and $\tilde{h} \leqslant 10^{-21}\,{\rm Hz}^{-1/2}$ over 80 Hz. Details are given in [9, 10].
- EXPLORER. The capacitive transducer and the SQUID were replaced in 1999 with a rosette geometry transducer, characterized by a high coupling (up to 0.05), and a commercial single-stage dc SQUID. The detector is again in data taking since the beginning of the year 2000. EXPLORER is now working at the level $h \simeq 4 \times 10^{-19}$, with a noise temperature of about 2 mK. The strain noise is $\tilde{h} \simeq 3 \times 10^{-21}\,{\rm Hz}^{-1/2}$ with a bandwidth of about 6 Hz, and $\tilde{h} = 10^{-20}\,{\rm Hz}^{-1/2}$ over a bandwidth of about 30 Hz. Cosmic ray detectors have been installed around the bar. Details are given in [11].
- NAUTILUS took data until February 2002, when it was warmed up for improvements. The bar was replaced by a new bar tuned at 935 Hz, twice the frequency where a pulsar, remnant of the SN1987A, was observed [12]. A new readout chain (the same as used for EXPLORER), plus a new suspension cable, to provide a more stable position setting, were mounted. The new run started in May 2003, with the detector cooled to 3.5 K. The resulting strain noise is $\tilde{h} \simeq 2 \times 10^{-21}\,{\rm Hz}^{-1/2}$ around 935 Hz, and $\tilde{h} \leqslant 10^{-20}\,{\rm Hz}^{-1/2}$ over about 30 Hz. The noise temperature is 1 mK, corresponding to $h = 2.5 \times 10^{-19}$. Details are given in [11]. Better results are expected when the system is cooled down to 0.1 K.
- NIOBE made its last run in February 2001 with a new very low noise (about ten times the quantum limit) microwave amplifier and worked at the level $h \simeq (4\text{–}5) \times 10^{-19}$ (which corresponds to the record noise temperature of 500 μK). Details are given in [13].

3. Results

All five resonant-mass detector groups formed the International Gravitational Event Collaboration (IGEC), during the second Amaldi conference in 1997 at CERN, and agreed

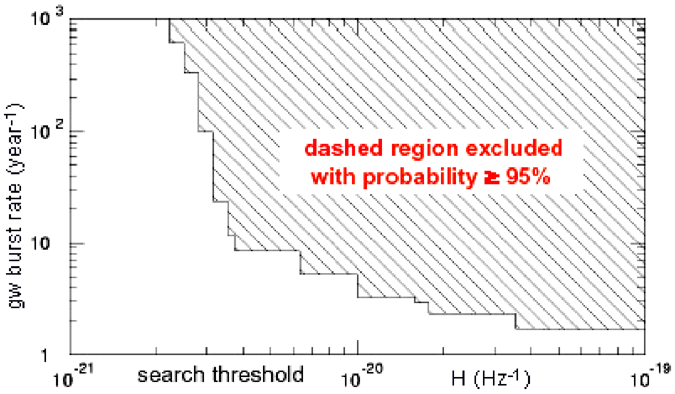

Figure 1. Upper limit for the rate of GW bursts detected by the IGEC observatory as a function of the amplitude search threshold, expressed in terms of the GW Fourier amplitude. For a conventional 1 ms burst, the corresponding strain amplitude is $h = 10^3$ H.

in a data exchange protocol to search for short GW bursts. The main goal of IGEC (see http://igec.lnl.infn.it/igec) is to standardize and simplify the data exchange between the groups and to maintain a continuous discussion on the analysis procedures. The analysis of the 1997–1998 data of all the detectors, released under the IGEC protocol [14], was recently followed by the analysis of all the data collected by the IGEC members in the years 1997–2000 [15]. Every group provided a file containing a list of events above a threshold corresponding roughly to a strain amplitude for a conventional 1 ms burst of $h \simeq 4 \times 10^{-18}$. This threshold corresponds roughly to $\simeq 10^{-2}$ solar masses converted in a GW burst at the galactic centre. The false alarm rate was lower than 1 per 10^4 years when three or more detectors were operating simultaneously. New upper limits for amplitude and rate of GW bursts have been set (see figure 1). It is interesting to note that, over the whole period (1460 days) at least one detector was operating for 90% of the time and at least two or three detectors for about 50% and 10% of the time respectively.

Other analyses using the data collected by the bar detectors in the last few years are as follows:

- A study of coincidences between EXPLORER and NAUTILUS [16]. The analysis is based on the comparison of candidate event lists recorded by the detectors in 2001. During this year EXPLORER and NAUTILUS were the only two resonant-mass detectors in operation and reached an unprecedented sensitivity. The analysis makes use of data selection based on physical characteristics of the detectors: the event energy and the directionality. The resulting small coincidence excess is discussed. The coincidence excess is found when the detectors are favourably oriented with respect to the galactic disc. This indication must be further investigated and understood [17, 18].
- A first cross-correlation analysis between two cryogenic detectors for the measurement of the GW stochastic background was published in 1999 [19] . The result (a value for the ratio of the energy density in GW to the critical energy density $\Omega(f) \leqslant 60$) was obtained with 17 h of the EXPLORER and NAUTILUS data, tuned in February 1997 at 907 Hz with an overlapping bandwidth of 0.1 Hz. A second analysis is in progress with the new data of EXPLORER and NAUTILUS, which can take advantage of the larger overlapping bandwidths and longer observation time.
- A search for monochromatic signals with the ALLEGRO and EXPLORER data puts the upper limits of $h = 4 \times 10^{-23}$ [20] and $h = 3 \times 10^{-24}$ [21], respectively, from the galactic

centre. An overall sky search has been performed by the ROG group in collaboration with the Polish Academy of Science in Warsaw and the Virgo Group in Rome. The analysis of 2 + 2 + 2 days of the EXPLORER data has already been done. An upper limit from the first two days analysis has been given [22]. Comparison of the candidates found in the three searches is under way. A coherent search for signals from the galactic disc or some globular clusters is planned in collaboration with the Albert Einstein Institute Max Planck in Golm, using the NAUTILUS 2001 data. Studies for the developments of hierarchical methods are also in progress in collaboration with the Virgo Group in Rome.

- Searches for correlations with the detectors of gamma ray bursts BATSE and Beppo-SAX have been performed using data of EXPLORER and NAUTILUS [23–25] and AURIGA [26].
- The passage of cosmic rays has been observed to give delta-like excitations to the NAUTILUS resonant mode [27] (roughly one per week at the reported NAUTILUS sensitivity, vetoed by a system of cosmic ray detectors). The correlation is very significant. Almost all NAUTILUS events are in agreement with the thermoacoustic conversion model. Some 10% of the events are very large at a rate greater than expected [28]. At present this effect seems to be due to the superconducting state of the bar [29]. An experiment is in progress at the INFN Frascati National Laboratories to test this temperature dependence [30].

4. Advanced acoustic detectors

Spherical detectors have been widely investigated and considered of interest by the ‘bar’ community because of their properties. In fact a single sphere is capable of detecting GWs from all directions and polarizations and to determine the direction information and tensorial character of the incident wave. Furthermore, for the same linear dimension, sphere diameter and bar length, the cross section of the sphere is larger than that of the bar by a factor equal to the ratio of the masses, which for the same material is about a factor of 20. The cross section of the second quadrupolar resonant mode is of the same order of magnitude as that of the first; using both modes, information on neutron star binary systems can be obtained. Studies and measurements essential to define a project of a large spherical detector, 40 to 100 tons of mass, cooled to 10 mK [31], have been made in the USA, Italy, the Netherlands and Brazil (see [32] and references therein). The burst sensitivity $h \simeq 4 \times 10^{-22}$, or, in spectral units, 3×10^{-23} Hz$^{-1/2}$ over a bandwidth of about 50 Hz, can be reached.

In the last few years many papers appeared discussing the realization of large spherical detectors [33–35] and the most significant technical barriers have been overcome. The possibility of alternative geometries has also been studied [36].

At present, small (about 60 cm diameter) spherical detectors are in preparation at Leiden University (Holland), in collaboration with the ROG group, and at São José dos Campos INPE (Brazil), with a predicted sensitivity in the 3 kHz range competitive with that of large interferometers [37, 38]. The expected sensitivity to GW bursts is $h \leqslant 10^{-20}$ within a bandwidth of about 200 Hz.

A new conceptual scheme for resonant-mass detectors has been recently proposed: the dual detector [39]. In the dual scheme, two resonant bodies are nested one into the other. The outer resonator has the quadrupolar GW sensitive resonant modes at lower frequencies with respect to the inner resonator. The GW excites the resonators in phase, but they respond about 180° out of phase. Therefore, as the displacement sensors measure the differential displacement of the two surfaces, the two signals sum and the dual detector is sensitive not only in a frequency range around the two quadrupole modes, but in the wider interval between them. At the same time the back-action force pushes the two masses 180° out of phase, so that, for the same reason, the back-action noise tends to subtract. Furthermore, by properly selecting the readout scheme, it is possible to cancel out both thermal and back-action noise contributions due to the non-quadrupolar modes, so that a flat response is obtained between the two resonances [40]. Different geometries have been proposed to implement the dual scheme: spherical and cylindrical dual detectors. For example, a SiC dual cylinder of 2.5 m diameter and length, with a non-resonant quantum-limited transducer, would provide a spectral sensitivity nearly flat at the level of about 10^{-23} Hz$^{-1/2}$ from 1.0 to 2.5 kHz, but giving up the advantages of the spherical shape. Such a spectral sensitivity would be better than that of the advanced interferometric detectors due by the end of the decade.

Both the spheres and the dual detectors, thanks to their distinctive intrinsic capabilities, would be complementary to interferometers, allowing the realization of very powerful GW observatories.

References

[1] Astone P *et al* (ROG Collaboration) 1993 *Phys. Rev.* D **47** 2

[2] Mauceli E *et al* (ALLEGRO Collaboration) 1996 *Phys. Rev.* D **54** 1264

[3] Blair D G *et al* (NIOBE Collaboration) 1995 *Phys. Rev Lett.* **74** 1908

[4] Coccia E and Niinikoski T O 1983 *J. Phys. E. Sci. Instrum.* **16** 695

[5] Astone P *et al* (ROG Collaboration) 1997 *Astropart. Phys.* **7** 231

[6] Prodi G *et al* (AURIGA Collaboration) 1999 *Proc. 2nd Edoardo Amaldi Conf. (CERN, Switzerland, 1–4 July 1997)* (Singapore: World Scientific) p 148

[7] Heng I S *et al* 2002 *Proc. 4th Edoardo Amaldi Conf. on Gravitational Waves (Perth, Western Australia, 8–13 July 2001)* (*Class. Quantum Grav.* **19** 1889)

[8] Johnson W *et al* 2003 Talk presented at *5th Edoardo Amaldi Conf. on Gravitational Waves (Tirrenia, Italy, 5–12 July 2003)*

[9] Taffarello L *et al* 2003 Talk presented at *5th Edoardo Amaldi Conf. on Gravitational Waves (Tirrenia, Italy, 5–12 July 2003)*

[10] Zendri J P *et al* 2003 Talk presented at *5th Edoardo Amaldi Conf. on Gravitational Waves (Tirrenia, Italy, 5–12 July 2003)*

[11] Visco M *et al* 2003 Talk presented at *5th Edoardo Amaldi Conf. on Gravitational Waves (Tirrenia, Italy, 5–12 July 2003)*

[12] Middleditch J *et al* 2000 *New Astron.* **5** 243

[13] Coward D *et al* 2002 *Proc. 4th Edoardo Amaldi Conf. on Gravitational Waves (Perth, Western Australia, 8–13 July 2001) Class. Quantum Grav.* **19** 1871

[14] Allen Z A *et al* (IGEC Collaboration) 2001 *Phys. Rev. Lett.* **85** 5046

[15] Astone P *et al* (IGEC Collaboration) 2003 *Phys. Rev.* D **68** 022001

[16] Astone P *et al* (ROG Collaboration) 2001 *Class. Quantum Grav.* **18** 243

[17] Finn L S 2003 *Class. Quantum Grav.* **20** L37

[18] Astone P *et al* (ROG Collaboration) 2003 *Class. Quantum Grav.* **20** S785

[19] Astone P *et al* (ROG Collaboration) 1999 *Astron. Astrophys.* **351** 811

[20] Hamilton W O 1999 *Proc. 2nd Edoardo Amaldi Conf. (CERN, Switzerland, 1–4 July 1997)* (Singapore: World Scientific) p 115

[21] Astone P *et al* (ROG Collaboration) 2001 *Phys. Rev.* D **65** 022001

[22] Astone P *et al* 2003 *Proc. 7th Gravitational Wave Data Analysis Workshop (Kyoto, Japan, 17–19 Dec. 2002) Class. Quantum Grav.* **20** S665

[23] Astone P *et al* 1999 *Astron. Astrophys. Suppl.* **138** 603

[24] Amati L *et al* 1999 *Astron. Astrophys. Suppl.* **138** 605

[25] Astone P *et al* 2002 *Phys. Rev.* D **66** 102002

[26] Tricarico P *et al* 2001 *Phys. Rev.* D **63** 082002

[27] Astone P *et al* (ROG Collaboration) 2000 *Phys. Rev. Lett.* **84** 14

[28] Astone P *et al* (ROG Collaboration) 2001 *Phys. Lett.* B **499** 16

[29] Astone P *et al* (ROG Collaboration) 2002 *Phys. Lett.* B **540** 179

[30] Bertolucci S *et al* 2004 *Class. Quantum Grav.* **21** S1197

[31] Frossati G and Coccia E 1994 *Cryogenics* **35** 9 (*ICEC Suppl.*)

[32] See, for instance, 1997 *Proc. 1st Conf. on Omnidirectional Gravitational Radiation Observatory (Sao José dos Campos, Brazil, 26–31 May 1996)* (Singapore: World Scientific)

[33] Coccia E *et al* 1996 *Phys. Lett.* A **219** 263

[34] Merkowitz S M and Johnson W W 1996 *Phys. Rev.* D **53** 5377

[35] Frossati G *et al* 1997 *Proc. Int. Conf. on Gravitational Waves: Sources and Detectors (Cascina, Italy, 19–23 Mar. 1996)* (Singapore: World Scientific) p 297

[36] Coccia E *et al* 1998 *Phys. Rev.* D **57** 2051

[37] de Waard A *et al* 2002 *Proc. 4th Edoardo Amaldi Conf. on Gravitational Waves (Perth, Western Australia, 8–13 July 2001) Class. Quantum Grav.* **19** 1935

[38] Aguiar O D *et al* 2002 *Proc. 4th Edoardo Amaldi Conf. on Gravitational Waves (Perth, Western Australia, 8–13 July 2001) Class. Quantum Grav.* **19** 1949

[39] Cerdonio M *et al* 2001 *Phys. Rev. Lett.* **87** 031101

[40] Bonaldi M *et al* 2004 *Class. Quantum Grav.* **21** S1155