Bar detectors: present and future

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Abstract

The status of operation of the five cryogenic bar detectors is reviewed, together with their capability for searches of galactic events in coincidence. The upgrades foreseen in short and medium term are summarized. Their rôle in a global network with the interferometric detectors under construction is discussed.

1. Introduction

For the first time a gravitational wave observatory is operating with a significant number of detectors to search for millisecond bursts of galactic origin. There are five resonant bar detectors currently in operation with comparable sensitivities: three I.N.F.N. detectors, the ultracryogenic AURIGA [1] and NAUTILUS [2] and the cryogenic EXPLORER [3], one N.S.F. cryogenic detector, ALLEGRO [4], and one A.R.C. cryogenic detector, NIOBE [5]. Recently the groups agreed on a procedure to exchange the data of the five detectors in order to start a significant search for impulsive events in coincidence, the IGEC [6], which is now producing the first results. It is estimated that in order to have a

Table 1. Bar main features. ALLEGRO, EXPLORER, NAUTILUS and AURIGA: material $Al5056$, mass 2.3 ton, Length 3 m, Diameter 0.6 m, Frequencies $895 \div 930$ Hz; NIOBE: material Nb, mass 1.5 ton, Length 2.75 m, Diameter 0.5 m, Frequencies $694 \div 713$ Hz.

	ALLEGRO	EXPLORER	NIOBE	NAUTILUS	AURIGA
Bar Working Temp. $[K]$	4.2	2.6	5	0.1	0.1
Mech. Quality Factor	1.5×10^6	2×10^6	20×10^6	3×10^6	3×10^6
$\tilde{h}$ at resonance $[Hz^{-1/2}]$	10×10^{-22}	6×10^{-22}	8×10^{-22}	3×10^{-22}	3×10^{-22}
Effective Bandwidth $[Hz]$	≈ 1	≈ 0.2	≈ 1	≈ 0.6	≈ 1.5
Burst Sensitivity h_{min}	8×10^{-19}	8×10^{-19}	10×10^{-19}	4×10^{-19}	4×10^{-19}
Duty Cycle	97%	50%	75%	60%	66%
$SNR > 4.5$ event rate $[d^{-1}]$	100	150	75	150	200

few detections/year, from sources as BH-BH merging binaries, an improvement of amplitude sensitivity by at least one order of magnitude over the presently achieved values is required. This can be confidently regarded as a medium term target. As the bars will be upgraded and the long baseline interferometers will start operation, they may well work together in a complementary way in a global network to determine the incoming direction of the wavefront and to test the specific properties of the Riemann tensor of the wave, i.e. transversality, tracelessness and light speed propagation [7], and in any case to increase the confidence of detection by the use of quite different detectors.

2. The cryogenic bars in operation and their foreseen upgrades

The sensitivity of current resonant bar detectors is peaked at the two quadrupolar resonant frequencies, corresponding to the two lowest modes of vibration of the bar-resonant transducer system, with an effective bandwidth which is actually larger than the mechanical resonance width. The effective bandwidth of the detector depends in fact on the interplay between narrow band brownian noise in the bar oscillator and the broad band noise in the amplification readout.

In Table 1 we report the main features of the cryogenic resonant detectors currently in operation, which are almost parallel oriented. The present typical effective bandwidth is ≈ 1 Hz, and the minima of the strain spectral density are in the range 3×10^{-22}. This implies that the minimum detectable gravitational wave burst is comparable for all the detectors. For an effective gravitational wave search, the availability of the detectors is as much relevant as the sensitivity, and therefore we report also the following parameters: i) the duty cycle of the detector, ii) its average burst sensitivity during the operating time and iii) the typical measured rate of events above a selected threshold. The rate of events typically measured at each detector above a selected threshold is a measure of the high energy tail of the event distribution, the part that is relevant for coincidence search. In fact, it is known that the distribution of the signal output of the detectors filtered for bursts shows a thermal brownian distribution and an excess of high energy events, which are generated by unknown local sources. The rates reported are of the order of $100/d$, and therefore $SNR > 4.5$ can be taken as a reasonable threshold in the current coincidence search, to allow for $< 10^{-5}/d$ probabilities of fourfold coincidences. Detectors demonstrate a high level of availability. However, their present sensitivity is still unsatisfactory. In fact, with respect to the expected loudest signals, the useful sensitivity currently limits the range to galactic sources, which have a very low statistical occurrence. For what concerns periodic signals or stochastic background, the achieved sensitivities are still well above the predicted signals, $\approx 10\Omega_{gw}$ [8]. Recently there is a strong indication that cosmic rays interact with bar g.w. detectors, as expected from earlier predictions [9]. One notices that AURIGA and NAUTILUS working at $He^3 - He^4$ refrigerator temperatures, show a somewhat better spectral sensitivity at resonance, while on the other hand the burst sensitivity is close to the others: the reason is that ultracryogenic operation is not yet fully exploited, since the final amplifier, the SQUID, is still too "hot", with energy resolution per unit bandwidth $\varepsilon > 3 \times 10^3\ \hbar$. Upgrades concern the operation, at somewhat lower $T \approx 50\ mK$ and higher $Q \approx 5 \times 10^7$, the integration of SQUIDs with $\varepsilon < 100\ \hbar$ [10] [11] and should also bring along a wider bandwidth of some 50 Hz. Similar performances are expected with parametric systems [12] and with optical readouts, which use interferometric methods at low temperatures [13]. The impulsive sensitivity should in all cases improve to $h_{min} \sim 3 \times 10^{-20}$. The duty cycle given in Table 1 concerns that allowed by ordinary cryogenic maintenance, not that due to major maintenances which require warm up of the system, with consequent interruption of operation for a few months. The daily $SNR > 4.5$ rate for impulsive events is a factor 3-5 larger than expected from a gaussian statistics and this is the unmodeled background mentioned above. With ALLEGRO it has been reduced, by enhancing the insulation against microseismicity and electrical disturbances [14]. With AURIGA attempts are made to use χ^2-test on the output to select against spuria [15], under the assumption that energy absorptions not originating in the bar, will propagate differently along the transduction chain. For the data acquisition and analysis, with AURIGA it has been introduced [16] [17] a fast, 5 kHz, A/D conversion of the signal from the final amplifier, synchronized within $1\mu s$ with UTC time, which allows on one hand a full storage of the raw

data and on the other hand a fully numerical analysis, with online adaptive filters. Presently the search and reconstruction of impulsive events gives amplitude, time of arrival [18] and χ^2-test vetos [15]. The noise appears to be a quasi-stationary gaussian process, with the parameters expected from the thermal noise acting on the bar-transducer system and the amplifier noise, plus the background noise. Almost all detectors are supposed to use soon data acquisition and analysis with similar schemes. In the near future, with the fast analysis, with the enhancements in sensitivity to $h_{min} = 3 \times 10^{-20}$ and the opening up of the bandwidth to $\Delta\nu = 50\ Hz$, the bars will keep a "watch" with the following characteristics:
– 16hours/day of coverage of the Galactic luminous mass
– detect down to $2 \times 10^{-5}\ M_{\odot}$ converted in g.w. at the Galactic Center
– background $< 10^{-6}$ fourfold coincidences/year (one detector will be under maintenance at any time)
– arrival time with $< 1\ ms$ of resolution
– source position in the sky within degs
– test of c-velocity propagation

3. The International Gravitational Event Collaboration, IGEC

At the 2nd Amaldi Conference W.O. Hamilton and W.W. Johnson for ALLEGRO, M. Cerdonio and S. Vitale for AURIGA, G.V. Pallottino and G. Pizzella for EXPLORER and NAUTILUS and D. Blair and M.E. Tobar for NIOBE signed an agreement to set up a data exchange protocol, the IGEC, for correlating the data from the detectors. The bars, by mutual agreement, were already oriented as much parallel as possible, to maximize the coincidence probability. Searches are for impulsive events. The goal of the IGEC is to standardize and simplify the data exchange and to maintain a continuous discussion on data acquisition and analysis procedures. Results of coincidence analysis are made public by unanimous consent. The core membership consists of groups producing gravitational wave data; so it is open to interferometric detectors groups, especially in their initial data taking. The current procedure is summarized as follows. Each group produces lists of impulsive events for each detector, above a declared threshold, chosen to have order of 100 events/day. The energy (in mK) of the event is given, together with its SNR and the UT time of occurrence. Coincidences are searched in a window of $\Delta T = 1s$, which corresponds to the inverse effective postdetection bandwidth of the detectors. The IGEC is analyzing data from 1997 and 1998, with order of few months of coincidental operation of $3 \div 4$ detectors. The results should be presented at the next GWDAW in Rome, Dec. 1999.

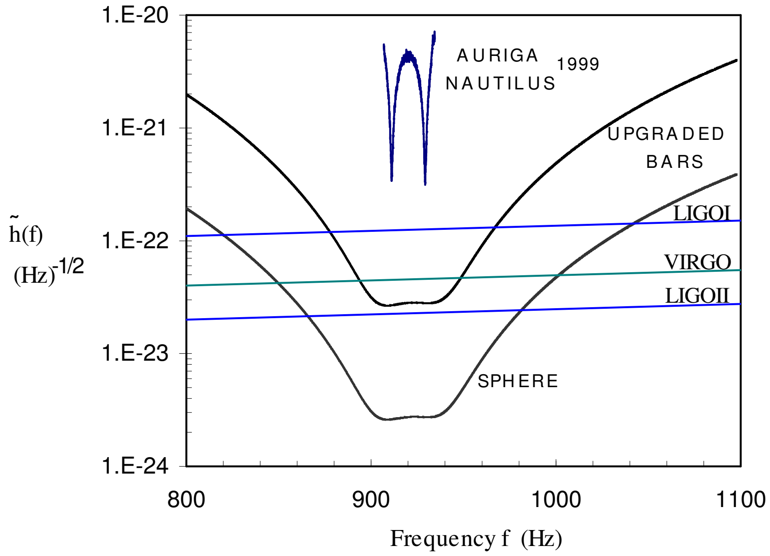

Fig. 1. Amplitude spectral noise density of bars and interferometers in the high frequency region; Bars: ultracryogenic bars as now in operation, prediction for upgraded bars with $T = 50\ mK$, $Q = 5 \times 19^7$, $\varepsilon = 10\hbar$, Sphere with $M = 230t$, $T = 50\ mK$, $Q = 5 \times 10^7$, $\varepsilon = 10\hbar$. Interferometers: predicted sensitivities for the initial LIGO, VIRGO and upgraded LIGO.

4. Longer term perspectives

Fig. 1 shows the spectral sensitivities of resonant and interferometric detectors in various stages.

It can be seen that, although in a narrow band, bars are currently showing a sensitivity close to that predicted for the initial operation of long base interferometers. Taking as "best bet", for a few per year detectable signal, that given by inspiral, merging and ring down of black-hole black-hole binaries of some 20 $M_\odot$ at a distance of 200 Mpc [19], current bars, with the quoted upgrades, may have enough sensitivity. In a 50 Hz band around 900 Hz they would have in fact a sensitivity similar to that of "advanced" interferometric detectors. This is possibly of relevance as, in the high frequency region, dealing with millisecond events, it may increase crucially the confidence of detection the fact that quite different detectors give coincidental observations. Also in principle it could be possible to solve the so called inverse problem, for searches of impulsive signals, by a straightforward extension of the exercise done for a "6 bars" network [7]. These solutions give signatures of symmetries of the g.w. Riemann tensor, as tracelessness and transversality, which could be used as vetos against spuria. As interferometers are intrinsically insensitive to the trace of the g.w. Riemann tensor, resonant detectors are crucially complementary in the global network. The most advanced resonant detector would be a spherical detector [20] of large, 300 *tons*, mass at mK temperatures [21]. It would enter the global network taking the former role of the bars in solving the inverse problem, with spectral sensitivity, Fig. 1, which would be matched probably only by a narrow banded "advanced" interferometer. Such a spherical detector would be intrinsically omnidirectional, would help in a distinctive way to detect coalescing binaries [22], and if placed appropriately close [23] to an inteferometer, would be measuring, in correlation with it, stochastic backgrounds at the level of $\Omega_{gw} \sim 10^{-7}$.

5. References

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