CRYOGENIC RESONANT DETECTORS OF GRAVITATIONAL WAVES: CURRENT OPERATION AND PROSPECTS

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1. Introduction

The detection of gravitational waves is a primary target for contemporary Physics because the radiation carries unique information on its astrophysical sources and can provide tests of General Relativity under extreme conditions. The experimental activity to open the era of a new gravitational wave astronomy has been developed since the early 1960's [1], and we can now witness that the current effort in this field is by far the greatest ever attempted. In fact, many cryogenic resonant detectors are already operating while long baseline interferometers are rapidly approaching their planned initial operation. Beside these earth based detectors, experiments are under way by Doppler-tracking satellites in the solar system [2] and the feasibility study for the interferometer in solar orbit [3] will soon start its experimental phase.

The current effort will be eventually crowned with success, and it is likely that the present detectors will play a crucial role for the advancement of this field. In fact, it is the first time that 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[4] and NAUTILUS[5] and the cryogenic EXPLORER[6], one N.S.F. cryogenic detector, ALLEGRO[7], and one A.R.C. cryogenic detector, NIOBE[8]. Very recently the involved research 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[9]. It is estimated that in order to detect gravitational waves emitted from sources which are expected to have a satisfactory statistical occurrence, such as supernovae and coalescing binaries in the Virgo cluster, an improvement of amplitude sensitivity by more than two orders of magnitude beyond the presently achieved values is required. However this jump in performance can be confidently regarded as a medium term target, since the path towards the quantum limited sensitivity for impulsive signals is now more clearly defined.

As the gravitational wave observatory improves and the long baseline interferometers start operation, it will be also possible 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[10]. In fact, all these aspects are necessary to provide a sound confidence of detection and a global network of detector is required for this purpose.

In the following Section we review the progresses of the resonant bar detectors currently in operation. Sect. 3 deals with the opportunities given by the present observatory for gravitational waves, in particular for bursts, with an insight on the expected medium term improvements. In Sect. 4 we overview the research and development activity currently pursued to approach the quantum limited sensitivity of resonant detectors and to increase their cross section and sky coverage. The relevant aspects of the future gravitational wave observatory made by resonant and interferometric detectors are outlined in Sect. 5.

2. The Operating Detectors

A recent review on the principle of operation of resonant detectors and on their sensitivity to predicted g.w. signals has been given in the previous G.R. Conference by Coccia[11]. Here we summarize only the main points required to discuss the performance of resonant detectors and some recent progresses which open new opportunities for burst detection.

2.1. PERFORMANCE OF THE OPERATING DETECTORS

Resonant gravitational wave detectors are extremely sensitive detectors of tidal or quadrupolar forces. The sensitivity is peaked at the quadrupolar resonant frequencies with an effective bandwidth much larger than the resonance width. The effective bandwidth of the detector depends crucially on the noise characteristics of the bar oscillator, its brownian noise, and of the amplification readout. The latter is composed of two unavoidable contributions: i) a back-action component, i.e. a noise source which acts on the resonating input load, and ii) an additive noise source to the detector output. The frequency range in which the noise force acting on the harmonic oscillators (i.e. brownian and back-action) dominates over the additive noise is the effective bandwidth, which is much wider than the resonance width of the oscillator.

The sensitivity of gravitational wave detectors is generally described in terms of the equivalent strain amplitude noise which produces the measured noise power spectrum at the detector output. A typical measured strain power spectral density $S_{hh}(\nu)$ for a resonant detector with a resonant displacement transducer, AURIGA, is shown in Fig.1. The two coupled harmonic oscillators, bar and transducer, produce two normal modes, whose frequencies are splitted and correspond to the minima of $S_{hh}(\nu)$. For a cylindrical antenna, the minimum value of $S_{hh}(\nu)$ (bilateral) per each normal mode is given by:

$$S_{hh,mode} = \frac{\pi}{16} \frac{k_B T_{e,mode}}{M_{mode} Q_{mode} \nu_{mode}^3 L^2} \tag{1}$$

where L is the bar physical length, $k_B T_{e,mode}$ is the mean energy of the mode, Q_{mode} and ν_{mode} are respectively the quality factor and the resonant frequency of the mode. M_{mode} is the effective mass of the normal mode when its dynamics is described in terms of the displacement of the bar end face. In fact, the total energy absorbed by the bar divides itself on the normal modes proportionally to $1/M_{mode}$ and energy conservation requires that $\sum_{modes} 1/M_{mode}$ equals the inverse of the effective quadrupolar mass of the antenna. In the simple case of a resonant detector with a well-tuned resonant transducer, each M_{mode} is half of the effective mass of the detector,

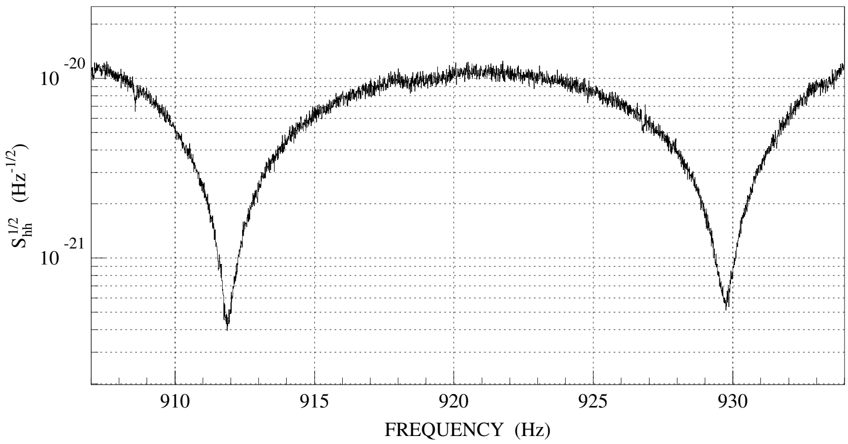

Figure 1. The strain noise power spectrum $S_{hh}^{1/2}$ for the detector AURIGA (June 1997)

i.e. $M_{mode} = M/4$ for a bar of physical mass M. We point out that $T_{e,mode}$ includes the brownian and the back-action contributions.

The sensitivity to monochromatic waves, such those expected from rotating non axisymmetric neutron stars, is easily calculated from the strain spectral density and the integration time t_m. The minimum detectable wave amplitude with Signal to Noise Ratio $SNR = 1$ at frequency ν is:

$$h = \sqrt{\frac{2S_{hh}(\nu)}{t_m}} \tag{2}$$

This sensitivity is largest for signals inside the effective bandwidth of the detector where the minimum detectable amplitude is:

$$h \approx \frac{1}{L}\sqrt{\frac{\pi k_B T_{e,mode}}{8 M_{mode} Q_{mode} \nu_{mode}^3 t_m}} \tag{3}$$

For what concerns the stochastic gravitational radiation, the measured $S_{hh}(\nu)$ is itself the experimental measurement achievable with a single detector, but it typically represents an upper limit much larger than any theoretical expectation. Crucial enhancements can be achieved by cross-correlating two nearby detectors. Neglecting the geometrical worsening factors related to the distance and relative orientation of two detectors, the minimum detectable power density $S_{gw}(\nu)$ of stochastic radiation is given by [12]:

$$S_{gw}(\nu) \approx \frac{\sqrt{\frac{1}{\Delta\nu}\int S_{hh,1}(\nu)S_{hh,2}(\nu)d\nu}}{\sqrt{t_m\Delta\nu}} \qquad (4)$$

where $\Delta\nu$ is the intersection between the effective bandwidths of the two detectors and t_m the integration time. The general case of two not nearby detectors with an arbitrary relative orientation is described in ref [13].

Whichever the signal buried in the detector output, it can be revealed applying an optimal linear Wiener-Kolmogorov filter, provided the detector noise spectral density at input and the signal shape are known. The SNR for the amplitude of a signal with Fourier transform $H(\nu)$ is then given by

$$SNR = \int_{-\infty}^{+\infty} \frac{\mid H(\nu) \mid^2}{S_{hh}(\nu)} d\nu \qquad (5)$$

All the operating detectors apply filters for δ-like signals, i.e. short bursts whose Fourier transform can be taken approximately to be constant, $H(\nu) = H_0$, over the effective bandwidths of the detectors. This kind of signals are expected from supernova collapses or final impact of coalescing binaries. In this case, resonant detectors measure directly the Fourier transform H_0 of the wave, whose minimum detectable value at $SNR = 1$ for a bar is given by

$$H_{0,min} = \frac{1}{8L\nu_0^2}\sqrt{\frac{k_BT_{eff}}{M}} \qquad (6)$$

where k_BT_{eff} is the minimum detectable energy and ν_0 is an average of the mode resonant frequencies. T_{eff} is known as the effective temperature and it has been the traditional parameter used to define the detector performance. This formula holds if an optimal filter for the H_0 of the δ-like signal is implemented, which is generally the case if the detector output is analyzed by a fully numerical procedure, as for AURIGA[14]. For the more traditional case in which the detector output is filtered for the signal energy, the achievable $H_{0,min}$ is larger by a factor $\sqrt{2}$: in fact the amplitude follows a gaussian distribution and therefore its square has a Boltzmann distribution with standard deviation equal to twice the square of the standard deviation of the amplitude.

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 $\approx 1\ Hz$, and the minima of the strain spectral density $\sqrt{S_{hh}}(\nu)$ are in the range $5\ \div 10\ \times 10^{-22}/\sqrt{Hz}$. This implies that the minimum detectable gravitational wave burst is comparable for all the

TABLE 1. Summary of the main parameters of the currently operating gravitational wave detectors. All the bars are equipped with a tuned resonant transducer resulting into two normal modes whose frequencies and quality factors during operation are reported. The subscript "ave" is relative to the average performance over the duty cycle. The reported values of duty cycle of the Al5056 bars give the fraction of the cryogenic run time during which the detectable H_0 at $SNR = 1$ is $< 5.5 \times 10^{-22} Hz^{-1}$. This figure corresponds to a threshold on the effective temperature of 20 mK. For NIOBE the duty cycle threshold† has been set to $7.7 \times 10^{-22} Hz^{-1}$ or $8mK$. The reported event rate is related to a threshold of $H_{0,thre} = 1.2$ or $1.7 \times 10^{-21}\ Hz^{-1}$ respectively for Al5056 bars and for NIOBE‡. These event thresholds are reasonable for the present coincidence search. The detectors are almost parallel and the reported misalignment is the amplitude of the angle between the bar axis and the perpendicular to the earth great circle close to the five locations.

	EXPLORER	ALLEGRO	NIOBE	NAUTILUS	AURIGA
bar material	Al5056	Al5056	Nb	Al5056	Al5056
bar mass $[kg]$	2270	2296	1500	2260	2230
bar length $[m]$	3.0	3.0	2.75	3.0	2.9
freq. ν_- $[Hz]$	905	895	694	908	912
freq. ν_+ $[Hz]$	921	920	713	924	930
$Q_\pm$ $[10^6]$	1.5	2	20	0.5	3
bar temp. $[K]$	2.6	4.2	5	0.1	0.25
$S^{1/2}_{hh,min}$ $[Hz^{-1/2}]$	6×10^{-22}	1×10^{-21}	8×10^{-22}	6×10^{-22}	5×10^{-22}
bandwidth $[Hz]$	≈ 0.2	≈ 1	≈ 1	≈ 1	≈ 1
duty cycle [%]	50	97	75†	50	60
$H_{0,ave}$ $[Hz^{-1}]$	4×10^{-22}	4×10^{-22}	5.5×10^{-22}	5×10^{-22}	4×10^{-22}
$T_{eff,ave}$ $[mK]$	12	11	4	15	10
event rate $[d^{-1}]$ above $H_{0,thre}$	150	100	75‡	150	200
latitude	$46°27'00''N$	$30°27'00''N$	$31°56'00''S$	$41°49'26''N$	$44°21'12''N$
longitude	$6°12'00''$	$268°50'00''$	$115°49'00''$	$12°40'21''$	$11°56'54''$
azimuth	39°	−40°	0°	44°	44°
misalignment	3°	6°	16°	2°	5°

detectors, being $H_{0,min} \approx 3 \div 6\ \times 10^{-22}\ Hz^{-1}$. 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 sensitivity during its operating time and iii) the typical measured rate of events above a selected threshold.

i) The duty cycle reported in Table 1 is the fraction of the cryogenic operating time in which the detectable H_0 at $SNR = 1$ is below a threshold of $5.5 \times 10^{-22} Hz^{-1}$ for the Al5056 bars and of $7.7 \times 10^{-22} Hz^{-1}$ for the Nb bar. Duty cycles range from 97% of ALLEGRO to the 50% of the younger ultracryogenic detectors and can be taken as a measure of the effective operating time. In the near future, it seems likely that ultracryogenic detectors will approach the high duty cycle of ALLEGRO. The selected thresholds are within a factor of 2 from the best typical sensitivity of the detectors and correspond to an effective temperature $T_{eff} = 20\ mK$ for the Al5056 bars and 8 mK for NIOBE. To simplify, it is assumed here and in the following that the data of each detector are filtered for the amplitude of the burst, as for AURIGA; that is a reasonable condition for all the detectors in the near future.

ii) The sensitivity for bursts averaged over the duty cycle is very close to the best typical sensitivity obtained by each detector. It can be considered as the useful sensitivity of the detector in a coincidence search and it is reported in Table 1 with subscript *ave*.

iii) 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 well known that the distribution of the signal output of the detectors filtered for bursts shows a thermal, in many cases brownian, distribution and an excess of high energy events, which are generated by unknown local sources. We report the typical rate of events at each detector whose amplitude is above $H_{0,thre} \simeq 1.2 \times 10^{-21} Hz^{-1}$ for Al5056 bars and $H_{0,thre} \simeq 1.7 \times 10^{-21} Hz^{-1}$ for NIOBE, that correspond typically to $SNR \approx 4.5$ over the average performance. The rates reported are of the order of $100/d$, and therefore $H_{0,thre}$ can be taken as a reasonable threshold in the current coincidence search, as it is shown in the following Section. The reported rates already include the vetoes for spurious events applied by each group. Moreover, these rates are affected by the efficiencies of the procedures that each group applies to search for events inside the detector's data. The efficiencies depend crucially on the capability to give a non biased estimator of the event amplitude. A procedure of almost complete efficiency has been implemented for the AURIGA detector[14] and is briefly presented in the following subsection.

It is clear from these facts that resonant detectors do demonstrate a high level of availability. However, their present sensitivity is still unsatisfactory, as is discussed in Sect. 3. In fact, with respect to the expected burst 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.

2.2. PROGRESSES CAPABILITIES FOR BURSTS DETECTION

The detailed shape of impulsive gravitational signals is unknown, but it is likely that any short burst will not show any structure inside the detectors bandwidths, at least as long as these are below 1 Hz per each normal mode and the detector modes are within $\approx$ 20 Hz to each other. It is for these reasons that the optimal filter of eq. 5 is generally built for the simplest impulsive signal, the δ-like event with a constant Fourier transform H_0 in the relevant frequency range. At this stage it seems meaningless to implement more complex filters. Anyway, the generalization of the δ-filter for a not so short signal of unknown shape has been already demonstrated in a wider-bandwidth detector[15] and therefore the data analysis procedures described in the following will keep their effectiveness.

A δ-like gravitational wave signal does not show any distinctive feature at a single detector; however, recent progresses on data acquisition and analysis[14] open now new opportunities for significant improvements in the confidence of detection. In particular, the fast data acquisition system synchronized to Universal Time allows optimal filtering procedures which give both the amplitude of the H_0 of the signal and its arrival time with sub-millisecond resolution[16]. Moreover, statistical tests on the compliance of the detected signal shape with a mechanical δ excitation of the bar can be used to veto spurious events of different origin[17].

The key hardware advancement has been the full implementation in the AURIGA detector of a fast data acquisition system with 5 kHz sampling frequency synchronized to Universal Time Coordinate by means of a Global Positioning System receiver equipped with a stabilized local oscillator[14]. The row data are then analyzed on-line with an optimal filter for both amplitude and arrival time of δ-signals and are fully registered on tapes for any future off-line analysis. The filter output is a zero mean signal sampled at 5 kHz with random amplitude and phase, oscillating at the average frequency of the bar+transducer modes with an autocorrelation time given by the Wiener time $\tau_{Wiener} \simeq 1/\pi\Delta\nu_{pd}$, where $\Delta\nu_{pd}$ is the effective bandwidth of the detector. A δ-like event shows up as a beating note with an envelope decaying with τ_{Wiener}: its maximum amplitude gives the H_0 and occurs at the arrival time of the event. The event search in the filter output is accomplished by searching for the symmetric central time of the beating note; if its amplitude overcomes a selected threshold and no other higher event is too close, the event is registered and the filter output is reconstructed in the continuous time domain with about $1\mu s$ resolution to measure its arrival time. In this way, the event amplitude is not underestimated and therefore the efficiency on event search above a threshold is maximum. More traditional procedures search for the maximum sample in a sequence of the output of the optimal filter for the energy of the δ-signal. This has two disadvantages: i) the phase information of the signal is lost and timing resolution is of the order of τ_{Wiener}, ii) the signal energy can be significantly underestimated and therefore not all events above a selected threshold will be caught.

We have already demonstrated[16] that there are two different contributions to the overall timing error of an event: one coming from the error on the determination of the phase of the filtered signal oscillating at the average frequency of the modes (the phase error σ_ϕ) and one from the ambiguity in the determination of the oscillating period of maximum amplitude (the peak error σ_p). The two contributions happen to be independent to a very good level of accuracy. Quantitatively they are very different, namely $\sigma_\phi \approx 173\mu s/SNR$ and $\sigma_p(k) \approx \pm kT_D/2 \approx k\ 540\mu s$ for the AURIGA detector, where $k = 0, 1, 2, \ldots, k_{max}$ and T_D is the period of oscillation of the signal. With these figures $\sigma_\phi << T_D/2$, so that the overall arrival time measurement gives a series of separated time intervals each one centered on $t_{meas} \pm kT_D/2$ with a standard deviation σ_ϕ. The value of k_{max} depends on the post detection bandwidth and on the SNR of the event. With a effective bandwidth of about 1 Hz, as for the present detectors, k_{max} will be reduced to 0 only with $SNR \geq 20$, thus reducing the series to a single interval.

Gravitational wave antennas are unavoidably affected by noise sources that can mimic a gravitational wave burst. Only part of these noise events is modeled, such as the brownian noise of the bar or the back action of the transducer chain, and their rate is expected to decrease with their amplitudes according to the normal distribution. In practice all the detectors are affected by non stationary noise sources that produce an extra number of large amplitude events. It is commonly believed that this extra-noise arises from local disturbances such as electromagnetic interferences, mechanical creeps, seismic activity, cryogenic liquid boiling and so on[18, 19]. In many detectors the number of events is reduced by $1 \div 10\%$ just rejecting those in coincidence with monitored local disturbances whose correlation with the detector output has been observed [18, 6, 19]. Another method particularly powerful to veto spurious events is based on testing the compliance of a candidate event with a δ-like gravitational wave induced signal. In the simplest version it is required that for each mode the energy innovation scales as the equivalent mass . However, thanks to the modern data acquisition systems, a more sophisticated procedure can also be used, checking the statistical compliance (χ^2-test) of the detected shape to the expected one induced by a δ-like gravitational wave[17]. This method is particularly efficient to reject extra noise introduced by the electromechanical transduction chain.

3. The Observatory for Gravitational Waves

3.1. BURSTS

The measurable Fourier transform H_0 of a burst can be transformed in a wave amplitude or a wave integrated energy only by assuming further characteristics of the wave: at least its central frequency ν_{sig} and its time length τ_{sig} or its frequency span. The more common assumptions are that the burst is composed by a sinusoidal oscillation at $\nu_{sig} \approx 1\ kHz$ lasting approximately one period, $\tau_{sig} \approx 1\ ms$. For this signal shape, the strain amplitude of the burst is

$$h \simeq \frac{2H_0}{\tau_{sig}} \approx \frac{2 \times 10^3}{s} H_0 \tag{7}$$

Therefore, the minimum detectable amplitude of each operating detector is typically $h_{min} \approx 6 \div 12 \ \times 10^{-19}$ at $SNR = 1$. As for a coincidence search, we show below that the confidence of detection requires to use a more reasonable threshold, close to $H_{0,thre} = 1.2 \times 10^{-21} Hz^{-1}$; the minimum detectable wave amplitude is therefore $h_{thre} \approx 2.4 \times 10^{-18}$.

The energy E_{gw} released in a gravitational wave burst at some distance R from the earth is related to the measurable H_0 by

$$H_0 \approx \sqrt{\frac{GE_{gw}\tau_{sig}}{2\pi^2 c^3 R^2 \nu_{sig}^2}} \approx \frac{1.5 \times 10^{-21}}{Hz} \frac{10^3\ Hz}{\nu_{sig}} \frac{10\ kPc}{R} \sqrt{\frac{E_{gw}}{10^{-2}c^2 M_\odot} \frac{\tau_{sig}}{10^{-3}s}} \tag{8}$$

under the above assumptions on the burst shape, plus linear polarization and as if the emitted radiation were isotropic. Therefore, $\approx 6 \times 10^{-3}$ solar masses converted in gravitational waves at the galactic center, $R \simeq 10\ kPc$, would give a signal of the order of the quoted $H_{0,thre}$ at the earth.

Since the operating detectors are parallel and rotating with the earth, they can monitor one polarization component from the galactic center for 70% of the time with a sensitivity greater than half maximum. We can conclude that the detection of bursts of galactic origin is at hand if the radiated energy is close to the more optimistic predictions. In the following we discuss how it is possible to achieve the confidence of detection and extract information on the source location.

The estimated visible mass inside the range of observation of a detector, M_{obs}, is shown in Figure 2 as a function of the signal threshold of the detector and of the energy released as gravitational wave burst. The reported mass data are taken from ref.[22]. The relationship between E_{gw} and h follows the assumptions on signal shape of eq.7 and 8. An Hubble constant of 75 $km/s/Mpc$ has been assumed. The profile of the visible mass versus

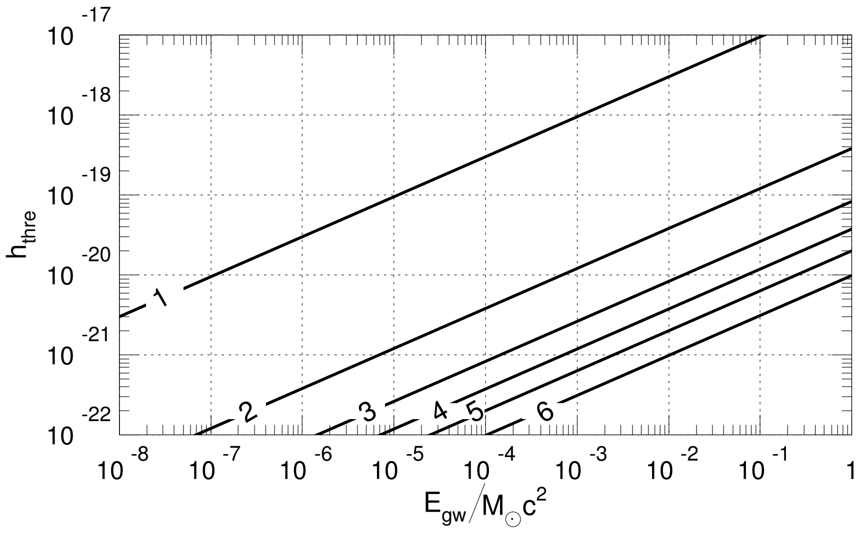

Figure 2. Some values of the visible mass inside the range of observation of a detector, M_{obs}, are shown as straight lines as a function of the energy emitted as gravitational wave burst (abscissa) and of the amplitude burst sensitivity of the detector (ordinate). The top continuous line corresponds to the Milky Way under the simplifying assumption that the mass be concentrated around the galactic center (**line n.1**: $M_{obs} = 0.4 \times 10^{12} M_{\odot}$ at $R = 10\ kPc$). The first significant increase come from Andromeda (**line n.2**: $M_{obs} = 1.1 \times 10^{12} M_{\odot}$ for $R \leq 0.77\ Mpc$). Other two close galaxies of the Local Group at $R = 3.5 \div 3.6\ Mpc$ contribute to further double the mass (**line n.3**: $M_{obs} = 2.2 \times 10^{12} M_{\odot}$ for $R \leq 3.6\ Mpc$). At higher distances the Virgo cluster is dominating M_{obs}: **line n.4**, $M_{obs} = 20 \times 10^{12} M_{\odot}$ for $R \leq 8\ Mpc$; **line n.5**, $M_{obs} = 1.2 \times 10^{14} M_{\odot}$ for $R \leq 15\ Mpc$; **line n.6**, $M_{obs} = 1 \times 10^{15} M_{\odot}$ for $R \leq 33\ Mpc$.

distance is very sharp as soon as the Virgo cluster is reached: M_{obs} overcomes $10^{13} M_{\odot}$ and $10^{14} M_{\odot}$ respectively at about 7 Mpc and 14 Mpc. At smaller distances the number of galaxies is small and $M_{obs} \approx 2.5 \times 10^{12} M_{\odot}$ in the Local Group ($R \leq 4.2 Mpc$). Figure 2 clearly shows that the amplitude sensitivity of present detectors should improve by almost two orders of magnitude to monitor the Andromeda galaxy with the same threshold on E_{gw} as currently achieved for the Milky Way. A further one order of magnitude improvement in amplitude sensitivity would then allow to achieve a very significant increase of M_{obs} of a further factor 20, leaving the threshold on E_{gw} unchanged for the galaxies at 8 Mpc. What resonant detectors plan to do to achieve this goal is discussed in Section 4.

In the present configuration of detectors more information than the simple signal detection could be achieved if we assume, according to General Relativity, that the gravitational waves propagate at light speed. In fact, in this framework, the source location in the sky could be reconstructed by measuring the delays between the signal arrival times at different detectors. Unfortunately, the majority of the present data aquisition systems are intrinsically unable to reach a time accuracy of the order of the light travel time among detectors. Moreover, as a consequence of the present limited bandwidths, modern fast data acquisition systems allow timing only with a large peak error at the most interesting $SNRs$, as discussed in the previous subsection. Therefore, two detectors would generally measure a series of separated possible values for the delay, each one corresponding to a circle in the sky as the possible source location. The number of circles is then limited by the assumption that delay must be less than light travel time. As the phase error is also present, each circle is a band whose width is proportional to SNR^{-1}. Using more than two detectors the incoming directions can be reduced to the intersections of the circles. Figure 3 show a sample of these circles for the AURIGA-NAUTILUS and AURIGA-EXPLORER couples of detectors assuming a signal of amplitude $SNR = 4$. The black spots represent the possible source directions given the three detectors operating in coincidence, summing up to a total of about 2% of 4π [20].

Up to now the upper limit on the gravitational wave impulsive event rate as a function of the amplitude comes from a coincidence analysis of the EXPLORER and ALLEGRO detectors during 6 months of 1991 [19]. With the five presently operating detectors this limit could be significatively improved as the noise generated events scale as $(\Delta t)^{n-1}$, where Δt is the coincidence temporal window and n the number of detectors in coincidence. It is also evident that a significative decrease of the time window from the present few tenths of second to the light travel time between detectors will decrease the false alarm rate by many orders of magnitude. This can be accomplished in the near future by extending to all detectors the arrival time capabilities. In this condition the noise generated coincidences rate of the observatory would be negligible compared with the expected galactic supernova explosion rate[20]. However, the predicted accidental coincidence rate is likely to underestimate the real one, since the detector noise is not stationary and the events appear often clustered instead of being randomly distributed in time. To reduce the number of non-gravitational coincidences a further veto on the data could be applied based on the requirement that for parallel detectors the measured amplitude differences should be of the order of the noise standard deviation[17] and within the calibration uncertainty.

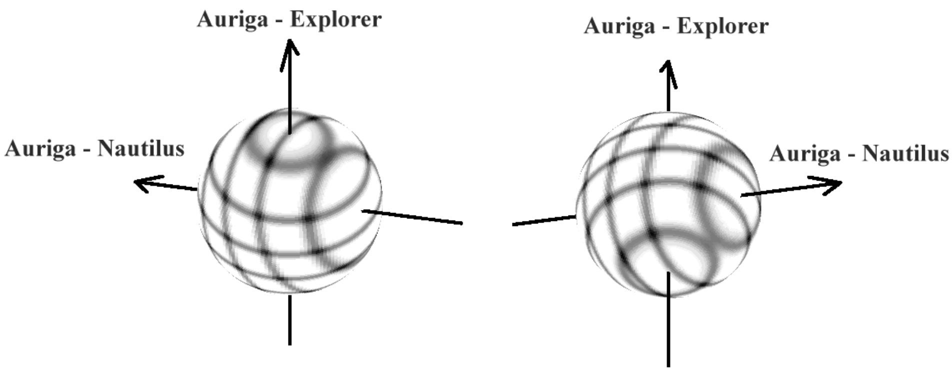

Figure 3. A map of the possible incoming wave direction on the celestial sphere for a sample signal of $SNR = 4$. It is assumed that the true delays between AURIGA-NAUTILUS and between AURIGA-EXPLORER are respectively 50 μs and 300 μs. The grey bands represent the allowable directions for any couple of detectors. The black spots are the possible source directions selected by the three detectors. The arrows represent the detectors baselines.

3.2. STOCHASTIC BACKGROUND

According to Table 1 the single detector upper limit on the stochastic background is $5 \times 10^{-22}/\sqrt{Hz}$. In principle a factor 10 could be gained for the detector AURIGA by cooling down the bar to 0.1 K if the mode temperature $T_{e,mode}$ approaches the thermodynamic temperature by decreasing the transducer electrical bias field. Further improvements can be achieved only by cross-correlating the output of two detectors for long times. However, since the correlated metric perturbation sensed by two different detectors has a wavelength shorter than the detector separation, the effective limit on S_{gw} are much worse than those calculated from eq. 4 and the general case is discussed in ref.[13]. Moreover the cross-correlation procedure is worthwhile only if the detectors resonant frequencies are the same within the post-detection bandwidths. Since this condition can be presently fulfilled only by the detectors NAUTILUS and EXPLORER, a first attempt has been done with these two detectors[23]. This experiment has demonstrated the effectiveness of the method but, due to the short integration time (a few hours), no significant improvement on the single antenna upper limit has been obtained. At last we point out that the presence of more than two detectors in the network does not provide an effective advantage, as the sensitivity for stochastic background scales as the square root of the detectors number.

3.3. MONOCHROMATIC WAVES

The strongest predicted sources of monochromatic waves are non axisymmetric rotating neutron stars, which should radiate almost monochromatic gravitational waves at twice their frequency of rotation, 2ω. These signals could be detected by the present operating detectors by integrating for long time spans (months), if 2ω falls in the effective bandwidth. Although many millisecond pulsars are known [24], no one matches the previous requirement. This reduces the candidate sources to non electromagnetic emitting neutron stars for which no information on sky position and spinning frequency are available. As a consequence, the signal shape at the detector location is unknown, since the central frequency is also phase and amplitude modulated by the earth motion with respect to the source. In practice many template should be used, one for each frequency and each source location, at the price of a tremendous increase of necessary computer resources.

A first attempt to measure monochromatic waves has been done by the ALLEGRO detector [25]. Here the problem is simplified assuming that the source is located in Tucanae 47, a globular cluster characterized by a large amount of pulsars. Data of three months of 1994 has been analyzed processing the stored data with an optimal Wiener filter. The resulting upper limit on the wave strength at frequencies close to the modes resonances is $h \leq 3 \times 10^{-24}$, corresponding to the most optimistic amplitude expected from a neutron star in Tuc47. Since the sensitivity is mainly limited by the local clock accuracy it is expected that a factor 10 in amplitude could be gained using more stable clock references, now easily available. In this regime however non stationary noise could limit the ultimate sensitivity. Finally work is in progress by P. Astone et al. [27, 26] to overcome the source location assumptions by building a data base of spectra averaged over a period of about 0.6 hours for the detectors NAUTILUS and EXPLORER. A signal would appear on different Fourier coefficients at different times, as a function of the possible source locations. In practice the sky is divided into a finite number of cells so that the possible fitting functions are limited to 20000.

4. Prospects for Near Future Improvements

There are basically two strategies to increase the minimal detectable gravitational wave amplitude, which are both currently pursued: increasing the bar cross-section and approaching the quantum limited sensitivity. The first attempts to maximize the gravitational wave energy absorbed by the bar against practical limitations. As the resonator cross section is proportional to $E \cdot Vol$ [28], where E is the antenna material Young modulus and Vol the resonator volume, this strategy leads to the construction of massive detectors with high stiffness materials. Up to now, the plans for the realization of the GRAIL detector[57] foresee a cross-section increase of about 40 over the present Al5056 bars. On the other hand, a sensitivity improvement could be achieved using lower noise amplifier-transducer chains. This procedure appears particularly relevant for the operating detectors as does not require heavy structural modifications. Moreover an energy sensitivity gain of $10^4 \div 10^5$ could be achieved, before reaching the limit imposed by quantum mechanics on standard detection schemes[29, 30]. In the following subsections we briefly overview the current attempts to improve the SNR at a single detector. However, we state that an effective sensitivity improvement can be obtained only if many detectors will operate at comparable sensitivities. In fact, a single detector cannot ensure by itself the confidence of detection of a gravitational wave signal with a non peculiar shape, and only as the detector number increases the effective threshold of the observatory can approach $SNR = 1$ while keeping the false alarm rate at an acceptable level.

4.1. TRANSDUCER-AMPLIFIER CHAIN

It is well known that the minimum detectable energy $k_B T_{eff}$ for an impulsive excitation of a monomode detector, i.e. a detector without resonant transducer, is

$$k_B T_{eff} = 2 k_B T_n \left\{ 1 + 2 \frac{1}{Q} \frac{T}{T_n} \frac{\nu}{\Delta\nu_{pd}} \right\}^{1/2} \tag{9}$$

where Q is the oscillator quality factor, T_n the amplifier noise temperature defined as $T_n = \sqrt{S_{FF} \cdot S_{xx}}/k_B$, S_{FF} and S_{xx} are respectively the back-action force and equivalent displacement power spectrum and $\Delta\nu_{pd}/\nu$ is the detector effective fractional bandwidth given by $\sqrt{S_{FF}/S_{xx}}/\pi\nu M$ for a monomode bar. Eq. 9 tells us that two requirements have to be fulfilled to maximize the sensitivity. First, the limit $k_B T_{eff} \approx 2 k_B T_n$ must be approached operating with low loss ($Q >> 1$), low T and/or broadband detectors. Second, T_n should be decreased as close as possible to the quantum limited value $T_n = \hbar\omega/k_B$ [30]. These considerations can easily be extended to the case of resonant detectors [34] giving similar indications. Further improvements on T_n would require quantum non demolition detection schemes[31].

The fractional bandwidth scales as the square of the transduction efficiency α, defined as the ratio of the bar motion amplitude to the transducer output electrical signal. Regardless of the used transducer there are always practical limitations to the α value for a monomode detector, so that typically $\Delta\nu_{pd}/\nu \approx 10^{-5} \div 10^{-7}$, which is too small to approach the $2k_B T_n$ limit even at very low temperatures and high quality factors. To overcome this limitation more mechanical oscillators are interposed between the bar and the amplifier [32, 33, 34]. If all the oscillators have the same resonant frequency of the main resonator a linear amplification of the antenna motion is produced at the last resonator. A significative enhancement of α is thus obtained. Using monomode transducers $\Delta\nu_{pd} \approx 1\ Hz$ has been achieved and in principle $\Delta\nu_{pd} \approx\ 50\ Hz$ could be obtained [35, 36]. A further bandwidth increase is expected using multimode transducers [37, 38, 33, 39, 40], but special care has to be taken on the resonators design to minimize the mechanical losses affecting the overall quality factor. A two mode transducer has been recently tested with good performances in terms of Q-factor by the Louisiana group [41]. Moreover the recent availability of low loss inductances [42] suggests the use of a electrical "LC" resonator, instead of a mechanical one. In particular, for a capacitive transducer this is naturally accomplished by means of the transducer capacitance and the primary inductance of the signal transformer to the SQUID. The resonant frequency of the electrical resonator can be adjusted during operation by moving a superconductive slab near the inductance [43]. Other strategies for the maximization of the α parameter has been proposed as for instance the use of levers as mechanical amplifiers [44, 45] or the use of parametric upconverter [46, 47, 48, 51] which are characterized by transduction efficiency proportional to the ratio of the high frequency pump to the low frequency signal.

For what concerns the amplifier noise, most of the operating detectors use d.c.SQUID devices as signal amplifiers with the operating noise temperatures about $10^4 \div 10^5$ times the quantum limited energy sensitivity. In order to improve the noise temperature special SQUIDs have to be designed, capable to work well below 1 K and having a complex geometry and read-out electronics. To our knowledge, the most promising SQUIDs recently realized for gravitational wave detection are the following:
i) M. Mueck and J. Gail (Giessen University) have specifically realized for the Auriga detector a dc SQUID with a coupled energy sensitivity $\epsilon_c \simeq 500\hbar$ at 1 kHz. The sensor operated in a closed loop configuration with room temperature electronics and showed no significant noise change reducing the temperature from 4.2K to 1.5 K, probably because the effect of the room temperature amplifier noise is dominating. Improvements are therefore expected with the integration of a cold transformer or a second dc SQUID stage.
ii) F.C. Wellstood and coworkers[49] have built a two stage SQUID on a single chip with a double input transformer. The intrinsic energy sensitivity is $\epsilon_i \simeq 35\hbar$ at 90 mK and 1 kHz. The coupled energy sensitivity should somewhat be higher than 100 $\hbar$ at 90 mK.

iii) The most recent paper published on the subject is that of P. Carelli et al.[50]. They realized a so called multi-washer SQUID with coupled energy sensitivity $\epsilon_c = 28\hbar$ at 4.2 K and $\epsilon_c = 5.5\hbar$ at 0.9 K. This SQUID has a very low SQUID inductance (15 pH) but a reasonably good coupling factor $k^2 \simeq 0.66$ with an input inductance of 0.5 μ H. The SQUID was tested in an open loop configuration and the output is amplified by a second dc SQUID.
Of course, the problem of integrating such sensitive devices into the real detectors without degrading the performance is still to be solved.

The NIOBE detector is equipped with an active parametric amplifier [51] with an overall noise temperature of few mK. The recent availability of ultra- low phase noise microwaves oscillators and of very low mechanical and dielectric losses sapphire cavities will probably push the sensitivity toward the quantum limit [52].

An alternative optomechanical transducer chain has been proposed [53, 36], in which the detection of the relative displacement between bar and resonant transducer is accomplished via a Fabry-Perot interferometer. Main noise contributions come from laser frequency and power fluctuations and from electronic noise of photodiodes. In principle one can actively stabilize laser power down to twice the shot noise level [54]. Laser frequency noise can also be reduced by frequency locking the laser source to a Fabry-Perot cavity [55]. At present the experimental activity is carried on by the AURIGA group in collaboration with a group at LENS, in Florence, with the aim to implement a complete transduction chain that would allow operation of AURIGA close to the quantum limit of sensitivity, using commercially available components.

The prospect for the next years is that the existing bar detectors will be upgraded to reach a burst sensitivity of $H_0 \approx 10^{-24} Hz^{-1}$ and an effective bandwidth of $\approx 50\ Hz$.

4.2. MASSIVE DETECTORS

A systematic investigation on the high thermal conductivity materials has shown that the $CuAl$ alloys are the best candidate materials for an ultra-low temperature massive detector [56], since they provide a compromise between the requirement of high quality factor $Q > 10^7$ and stiffness materials and the availability of considerable quantity at an acceptable cost. Using this material, modern spherical detectors [57, 58, 59], could increase the cross section more than one order of magnitude. In particular the GRAIL detector, whose experimental feasibility study has just started, could be a $3-meter$ diameter $CuAl$ (94/6) sphere of about 110 ton with a cross section about 40 times the one of the others ultra-cryogenic detectors (NAUTILUS, AURIGA) [60].

Finally we remark that the interaction of the cosmic rays with the resonator body [69] could make useless any improvement beyond expected near future sensitivity. In fact, although these spurious events could be rejected through anti-coincidence with cosmic ray telescopes [67], the present predictions for very sensitive detectors, as for GRAIL [65, 66, 68], give an unacceptably high dead time. Then, if the efficiency of cosmic ray excitations will be definitively confirmed by experiments [68], future detectors could be forced to operate underground.

5. The future of g.w. detection

Looking forward to the future of gravitational waves detection we can forecast some important steps toward the first implementation of a reliable networked observatory. i) The predicted bandwidth widening of present resonant bar detectors will allow much more precise absolute timing of signals, opening the way to inter-detector delay measurement and source position reconstruction. ii) By the turn of the century upgraded resonant detectors will operate together with long arm interferometers [61, 62, 63, 64] enhancing and increasing the amount of information obtainable from astrophysical sources and allowing for tests of gravitational waves distinctive properties such as light-speed propagation, transversality and tracelessness [10, 20]. Notice that by then an almost isotropic sky coverage can be obtained simply by rotating one resonant bar in its horizontal plane [20]. iii) In the mid term planned spherical detectors will join the network of worldwide detectors. They will give consistent improvements to the observatory performances as they promise sensitivity increases ($h_{burst} \approx 10^{-22} \div 10^{-23}$), omnidirectional sky coverage[70] and estimation of source position and polarization[71].

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