The Gravitational Wave Burst Observatory: Present State and Future Perspectives

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The expected performances of the gravitational wave observatory composed by the five resonant detectors currently in operation are discussed. The potential near future improvements are also examined assuming that the noise properties of the up-graded resonant detectors will be in agreement with predictions. With the initial operation of long baselines interferometers a substantial improvement in the burst search is expected.

1. INTRODUCTION

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. In fact, there are five resonant bar detectors currently in operation with comparable sensitivities: three I.N.F.N. detectors, the ultracryogenic AURIGA and NAUTILUS[?, ?] and the cryogenic EXPLORER[?], one N.S.F. cryogenic detector, ALLEGRO[?], and one cryogenic A.R.C. detector, NIOBE[?]. 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 coincidences[?]. Future perspectives are very promising because of the expected improvements in sensitivity of the resonant detectors and because of the planned initial operation of the long baseline interferometers GEO 600, LIGO and VIRGO. As the gravitational wave observatory improves, it will be possible to detect gravitational radiation from extragalactic sources, to determine its direction of propagation and to test the specific properties of the Riemann tensor of the wave, i.e. transversality, tracelesness and light-speed propagation[?]. In fact, all these aspects are necessary to provide a sound confidence of detection and a global network of detectors is required for this purpose.

The ability of the currently operating observatory to detect gravitational bursts and to solve the inverse problem are discussed in Section 2. In particular, we show the relevance of a high resolution measurement of the burst arrival time at each detector because it allows to locate the source and to decrease significantly the false alarm rate for coincidence detection. In Section 3 we describe the expected improvements of a global observatory composed of the long arm interferometers together with the resonant detectors.

2. PRESENT STATE OF THE GRAVITATIONAL WAVE OBSERVATORY

The configuration of the gravitational wave observatory, as presently operating, consists of five

Table 1
Locations of the five currently operating bar detectors. The misalignment gives the modulus of the angle between each detector axis and the direction normal to the earth great circle closest to all the 5 sites.

	Location	Latitude	Longitude	Azimut	misalign.
ALLEGRO	$Baton Rouge, LA, USA$	$30°27'00''$ N	$268°50'00''$	$-40°$	$6°$
AURIGA	$Padova, Italy$	$44°21'12''$ N	$11°56'54''$	$44°$	$5°$
EXPLORER	$Geneva, Switzerland$	$46°12'00''$ N	$6°12'00''$	$39°$	$3°$
NAUTILUS	$Roma, Italy$	$41°49'26''$ N	$12°40'21''$	$44°$	$2°$
NIOBE	$Perth, Australia$	$31°56'00'$ S	$115°49'00''$	$0°$	$16°$

resonant bars, almost parallel to each other, as reported in table 1. In fact, the detectors are perpendicular within a few degrees to an earth great circle close to their sites. This choice maximizes the chances of coincidence detection and the confidence of detection relies mainly on the minimization of the false alarm rate. The price paid is that the present observatory is not isotropically sensitive and no distinctive properties of a gravitational wave can be tested.

For each operating detector the minimum detectable amplitude for a millisecond pulse is $h_{min} \simeq 5 \times 10^{-19}$. The power spectral density in strain referred at input shows minimum values of the order of $\tilde{h} \simeq 5 \times 10^{-22}/\sqrt{Hz}$ with effective bandwidths $\Delta\nu_{pd} \simeq 1Hz$ for each detector. For what concerns the duty cycle, there are significant differences among detectors; for example the ultracryogenic detector AURIGA noise performance is about two thirds of the time within a factor of two from the above figures, while for ALLEGRO the duty cycle has been substantially larger.

This level of sensitivity should allow the detection of the strongest gravitational wave bursts of galactic origin, since a Signal to Noise Ratio $SNR = 4$ corresponds to $\simeq 5 \times 10^{-3} M_{\odot}$ converted into gravitational waves at the galactic center. $SNR = 4$ gives an acceptable observatory false alarm rate, as discussed in subsection 2.2.

In this respect, one should take into account that the antenna pattern of the present observatory follows the earth rotation and thus is able to cover the galactic luminous mass for two thirds of the time with a sensitivity greater than half maximum. In the case of linearly polarized signals the detection probability is a factor of two worse than that, since the observatory is sensitive to only one polarization.

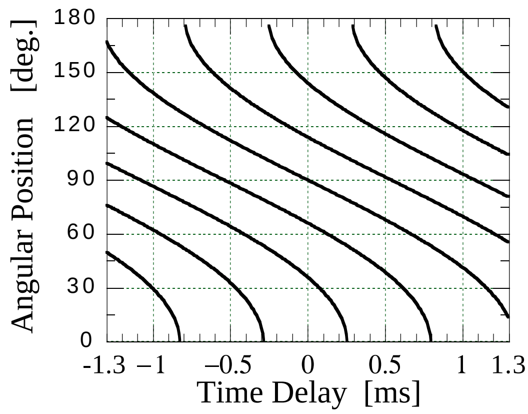

Figure 1. The reconstruction of the angular position θ of the source from the baseline of AURIGA-NAUTILUS as a function of the measured time delay between detections at those sites.

Significant improvements of detection confidence could be easily achieved by implementing in each operating detector a fast data acquisition system synchronized with the Universal Time Coordinate, similar to that already operating for the AURIGA detector[?]. In fact, such a system allows to measure the arrival time of a burst with sub-millisecond accuracy, a capability which has at least two relevant consequences: i) to locate the gravitational wave source, as discussed in the following subsection, and ii) to squeeze significantly the time window in which meaningful coincidences can be found and therefore to decrease significantly the probability of false alarms, as shown in subsection 2.2. Major improvements on the sensitivity and the timing capabilities of the observatory can be achieved within a few years by realizing new transducer-amplifier chain, as discussed in subsection 2.3.

2.1. Source location

Assuming that the gravitational signal travels at the speed of light, the position of the source in the sky can be determined by measuring the time delays between detections of the same burst at the existing detectors. How well this can be done depends on how well each detector can measure the burst arrival time. The timing accuracy for a signal superimposed to a Gaussian noise has an intrinsic limit [?, ?] that can be reached [?] using the fast data acquisition system as presently operating for the AURIGA detector[?]. In this case, the output of the optimal filtering procedure for δ -like signals shows an oscillating pattern at twice the natural frequency of the detector, $2/T_D$, whose amplitude is maximum at the arrival time and decays exponentially with time constant $\tau_{pd} = 1/\pi\Delta\nu_{pd}$ away from it. The total timing uncertainty can be divided into two contributions [?]: i) a phase error σ_ϕ related to the uncertainty on the phase of the oscillating pattern $\sigma_\phi = T_D/2\pi SNR \simeq 173\ \mu s/SNR$ for the present INFN detectors, where SNR is the Signal to Noise Ratio of the burst; ii) a peak error $\sigma_m \simeq mT_D/2$, with m integer, due to the ambiguity on the recognition of the peak of maximum amplitude. σ_m decreases with increasing the post detection bandwidth and becomes negligible for $\Delta\nu_{pd} > 50Hz$. For the present detectors with $\Delta\nu_{pd} \simeq 1Hz$, however, the peak error is generally relevant and it becomes negligible only for $SNR > 10$. Therefore, the timing measurement at each detector has about $2m + 1$ possible solutions, which are separate from each other since $\sigma_\phi \ll T_D/2$ even for small SNR. This timing ambiguity affects obviously the estimate of delays of detection between couples of detectors. For the present observatory the reconstruction of the location of a gravitational wave source will generally give several spots in the sky.

Let us first discuss the simple case of a couple of resonant detectors at a distance Δl. If their natural frequency is sufficiently close to make negligible the difference between $mT_D/2$ of the detectors with respect to the phase error, as in the case of the INFN detectors AURIGA, NAUTILUS and EXPLORER, the only significant effect of the peak error is to allow multiple solutions on time delay measurement, each one with uncertainty given by the phase error. This fact affects similarly the reconstruction of the angle θ between the direction of propagation of the gravitational pulse and the baseline between the detectors, given by

$$\theta_n = arcos\left(c\frac{\Delta t \pm nT_D/2}{\Delta l}\right) \tag{1}$$

where Δt is the measured delay between the arrivals of the pulse at the two detectors and n is an integer ranging approximately from $-\sqrt{2}m$ to $+\sqrt{2}m$. Each θ_n value will show an uncertainty due to the phase error σ_ϕ. For any couple of detectors, the problem of reconstructing the incoming direction is completely axis-symmetric around the baseline between the two detectors, so that each value of θ_n actually determines an entire circle in the sky. Moreover each circle has a finite width, due to the phase error σ_ϕ and we can easily compute the solid angle $\delta\Omega = \delta(cos\theta)\delta\phi$ into which the source position will be placed for each n value. In fact,

$$\delta\Omega = 4\pi\frac{c \cdot 173\mu s}{\Delta l \cdot SNR} \tag{2}$$

since $\delta\phi = 2\pi$ because the axis-symmetry and $\delta(cos\theta) = 2c\sigma_\phi/\Delta l$.

The source of a signal with $SNR = 5$ will be located inside a circular area of just 2.6% of the entire solid angle 4π, for each possible value of n.

Eventually, the maximum number of the physically possible θ_n for the incoming direction of a gravitational wave can be further reduced since Δt must be within $\pm\Delta l/c$. This is particularly relevant for not too far apart detectors and small SNR. In particular, the ultracryogenic detectors AURIGA and NAUTILUS are only 397 km apart, reducing the number of possible values for θ_n to just 5 for any measured value of Δt (see figure 1). The total solid angle of the possible source locations for $SNR = 5$ is then 1.6 $sterad$, that is 13% of the entire solid angle. Similarly, the baseline between the detectors AURIGA and EXPLORER is 455 km and therefore there are at most 6 possible θ_n.

The measurement of more than one time delay in the detection of a burst at different sites allows to further limit the possible source locations to the intersections of the solid angles given by each couple of detectors. In figure 2 we show an example of how well the three INFN detectors could reconstruct the location of a source. The angle between the baselines AURIGA-EXPLORER and AURIGA-NAUTILUS is 112.6 deg and there are about 45 possible source locations in the sky for one pair of measured time delays, corresponding to a total solid angle of about 2% of 4π. At present, the other resonant detectors ALLEGRO and NIOBE are too far away to significantly improve this performance, unless the SNR is high enough to limit the peak error on timing to a few peaks. As we said, this requirement on SNR will become less stringent as the post-detection bandwidth of every detector increases[?]. Moreover, the perspectives will improve drastically in the future when new detectors will begin operation, as discussed in Section 3.

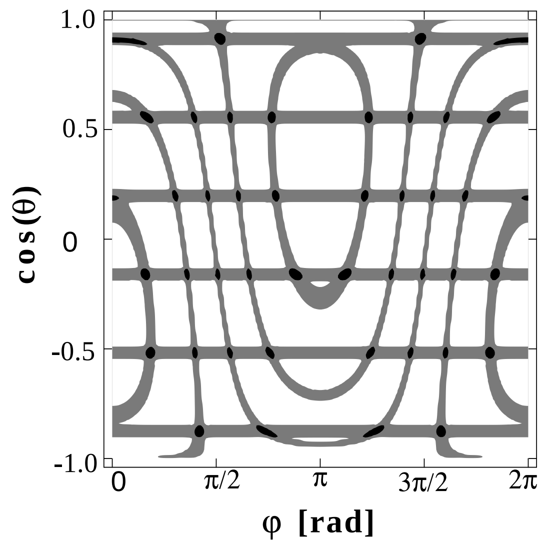

Figure 2. An example of an arbitrary reconstruction of the angular position of the source by the three INFN detectors. Possible source locations are shown as the darker spots at the intersections. The reference frame is chosen attached to the detectors so that θ is the angle with the AURIGA-EXPLORER axis and ϕ is the angle in the orthogonal plane. A burst amplitude such that $SNR = 5$ has been assumed.

2.2. False alarm rate

The simplest coincidence method compares the arrival times of the events detected at each antenna with an amplitude above a selected threshold. A coincidence occurs when the events delay is consistent, within the timing accuracy, with the light travel time. Obviously a false alarm rate of coincidences is produced by noise fluctuations at each detector. Therefore gravitational waves searches are meaningful only for the event amplitudes whose associated network false alarm rate is much less than one event in the observation time.

The calculation of the false alarm rate in the observatory requires at first to estimate the number of events occurring in an observation time T above an amplitude threshold. As previously mentioned the filter output of the detector for a burst excitation produces an oscillating pattern lasting approximatively $2\tau_{pd}$. Care must be taken in order not to miss neither to overcount a single event. For example sampling the filtered output at constant rate $\Delta t > \tau_{pd}$ produces an underestimation of the event count because events occurring in the "blind" time can be decreased significantively in amplitude at the sampling time. On the contrary a fast sampling rate $\Delta t \leq \tau_{pd}$ produces an overestimation of the events count because, for a time $\approx \tau_{pd}$ around the arrival time, a single gravitational event produces many local maxima above the threshold. For this reason each group has developed a procedure for event detection (see e. g. [?]) looking for the absolute maximum of the filtered output after continuous reconstruction in the time domain and disregarding nearby maxima due to the same event.

Let's consider for instance the procedure developed for the AURIGA detector: here the output of the Wiener filter is calculated assuming the signal has arrived at time t_w. The parameter t_w is then continuously changed until the filter output reaches its maximum value, which is equal to the signal amplitude when t_w equals the true signal arrival time. This procedure would not be accurate if another similar event would occur within a post detection time. The prediction of the number of events generated by the noise is not straightforward, because the noise is not made up of τ_{pd} separated events and in general has a transfer function different from that of the gravitational signal. In table 2 the results of a Monte Carlo calculation using the same parameters as the AURIGA detector are summarized. A rate of ≈ 100 events per day imposes a threshold of about $SNR = 4 \div 5$ on a single detector.

If the coincidence window is Δt, the number of coincidence $N_{n,T}$ between n detectors is

$$N_{n,T} = N_T \cdot A_n \left(\frac{2 N_T \Delta t}{T} \right)^{n-1} \tag{3}$$

where A_n is a positive number less or equal than one ($A_2 = 1$, $A_3 = 3/4$, $A_4 \simeq 0.5$). The smaller is the temporal window Δt the fewer are the coincidence counts. The present network arrival time accuracy is about $\tau_{pd} \approx 0.4\ s$ so that, as reported in table 3 (columns 'W') at least four detectors are required to operate in coincidence to decrease the accidental events rate to an acceptable values for $SNR = 4$. A remarkable improvement could be obtained using fast data acquisition system, where timing capabilities narrow the coincidence time window to the sub-millisecond region. However if the incoming wave direction is unknown the coincidence window should be the maximum light travel time among the detector sites. In columns T of table 3, the predicted false alarm rate using such timing capabilities is presented. It is evident that acceptable false alarm rate could be obtained using only 3 of the 5 network detectors in coincidence. In principle, using four detectors, threshold as low as $SNR = 3$ could be also monitored, in practice non-modeled noise (see below) may forbid this.

Each of the gravitational wave detectors now in operation is affected by non modeled extra noise sources. For a single detector this corresponds to an excess of events particularly relevant for high SNR. Many experimental efforts have been devoted to reduce extra noise sources [?] or to reject spurious events [?] in single detectors. In particular the use of fast data aquisition systems allow the reconstruction of the signal form in the time domain. The candidate events can be thus selected testing the statistical compatibility (χ^2-test) of the measured signal shape with the specific form expected for a true gravitational wave signal [?].

Although time coincidences between different detectors appear extremely efficient to reject the residual non gaussian events [?], the prediction of table 3 could be only a lower limit of the false alarm rate. To improve the confidence of detection of gravitational waves, a further veto procedure could be applied. Indeed as in the present network configuration the bars are almost parallel it is unlikely that a gravitational wave would be detected at the different bars with amplitude differences bigger than the single detector standard deviation h_{min}. Events in coincidence but with amplitude differences bigger than few h_{min} are thus rejected by a χ^2 test on the observatiry [?]. This procedure is expected to be particularly efficient for high amplitude signals unless calibration errors become relevant.

2.3. Near future improvements of the present observatory

The energy resolution of the operating detectors is about 10^5 times the ultimate limit imposed by the so called Standard Quantum Limit (SQL) [?]. This is apparently due to the noise performance of transduction chains and is almost the same for all detectors, in spite of the different techniques implemented by the different groups. The cause of this limitation is not yet fully understood, since on the basis of previous bench tests of single components of the chains the predicted noise performances are better by a factor between 10 and 100 in energy. Therefore, in the near future, intensive efforts have to be

Table 2
Monte Carlo prediction of the events numbers occurring in one resonant detector for an observation time of one day under gaussian statistics. The computation is performed using the AURIGA parameters.

SNR	≥ 3.5	≥ 4.0	≥ 4.5	≥ 5.0	≥ 5.5	≥ 6.0
$Events/day$	1453	359	60	8	0.7	0.05

Table 3
Number of false alarms per year for different gravitational wave burst amplitudes h_b as a function of the number of the detectors operating in coincidence. We have assumed that $h_{min} = 5 \times 10^{-19}$, so that the three rows correspond respectively to $SNR = 3, 4, 5$. The columns W refer to the present time window of $2\tau_{pd} \approx 0.8$ sec, while the columns T to a time window of 20 $msec$.

	2 Bars		3 Bars		4 Bars	
h_b	W	T	W	T	W	T
$1.5 \cdot 10^{-18}$	$9.3 \cdot 10^{4}$	$2.3 \cdot 10^{3}$	$4.8 \cdot 10^{3}$	$2.9 \cdot 10^{0}$	$2.0 \cdot 10^{2}$	$3.1 \cdot 10^{-3}$
$2.0 \cdot 10^{-18}$	$8.7 \cdot 10^{2}$	$2.2 \cdot 10^{1}$	$4.3 \cdot 10^{0}$	$2.7 \cdot 10^{-3}$	$1.7 \cdot 10^{-2}$	$2.7 \cdot 10^{-7}$
$2.5 \cdot 10^{-18}$	$4.3 \cdot 10^{-1}$	$1.0 \cdot 10^{-2}$	$4.8 \cdot 10^{-5}$	$3.0 \cdot 10^{-8}$	$4.3 \cdot 10^{-9}$	$6.8 \cdot 10^{-14}$

devoted to the realization and implementation of transducer-amplifier chains effectively operating at their expected sensitivities with the target of approaching a SQL performance. The improvement of the energy resolution to about 100 time the SQL for the present resonant bars would lead to a minimum detectable amplitude for a millisecond pulse $h_{min} \approx 3 \times 10^{-20}$ and to $\Delta\nu_{pd} \approx 50Hz$. This large bandwidth would allow the measurement of the arrival time with negligible peak error at any interesting SNR. Therefore, with at least three independent time delays, the source could be unambiguously located and the many spots in figure 2 would be reduced to only one. If all detectors were operating, the propagation speed of the wave would be measured too. With the above strain sensitivity, $SNR = 4$ would correspond to $\approx 2 \times 10^{-5} M_\odot$ converted in gravitational waves at the Galactic Center. For stronger sources the interesting observational range would then be extended to the Local Group of galaxies.

3. FUTURE PERSPECTIVES

The final step toward a gravitational wave observatory for burst signals would probably be the integration, on a single network, of upgraded bars, long baseline interferometers (LIGO[?], VIRGO[?], GEO[?], TAMA[?]), and possibly massive omnidirectional spherical detectors (GRAIL[?]). The difference of bandwidth between resonant detectors and interferometers is not a crucial point for the burst search as the signals we are looking for have no structure within the detectors bandwidth. The advantage of such a network of detectors would be two-fold: i) the network would have an almost isotropic sensitivity in direction and polarization of incoming bursts as the detectors would be no more parallel; ii) one would be able to test distinctive properties of a gravitational wave, such its velocity of propagation, ist transversality and tracelesness.

It has already been demonstrated [?], using a model of six bars orientated as the symmetry axes of a dodecahedron, that the so-called inverse problem can be solved and a linear veto based on the tracelessnes of a gravitational wave can be exerted. This solution can be easily extended to any network of gravitational wave detectors. In fact the response of a detector $X^\alpha(t)$ to linearly polarized radiation coming from a direction $\vec{k}$ can be written as

$$X^\alpha(t) = h_b \, \mathcal{C}^\alpha \; f(t - t_0 - \vec{r}^\alpha \cdot \vec{k}/c) \tag{4}$$

where $\mathcal{C}^\alpha = R_{ij}(n^i n^j)^\alpha$ or $\mathcal{C}^\alpha = R_{ij}(n^i n^j - m^i m^j)^\alpha$ are respectively the bar and interferometer figure patterns, $\vec{r}^\alpha$ is the radius vector of the $\alpha - th$ detector in a geocentric coordinate system, t_0 is the arrival time of the signal at the coordinate origin, n^i and m^i are the directions of the bar axes and of the interferometer arms. Here the 3×3 symmetric matrix R_{ij} represents the wave polarization tensor in the geocentric frame which carries all the distinctive symmetries of the gravitational wave Riemann tensor. Using the time delay information we can invert the above equations with the detector responses shifted on the same wavefront, giving an estimate of the tensor $h_b R_{ij}$. It is worth to notice that, being $(n^i n^j - m^i m^j)$ a traceless tensor, the trace of R_{ij} cannot be estimated by interferometers or spheres alone, and therefore bars would play a crucial role in the network.

As an example, we have calculated the sky coverage of the network made of 4 of the interferometers currently in construction (LIGO-LA, VIRGO, GEO, TAMA) and 2 bars (ALLEGRO, AURIGA) assuming a similar burst sensitivity for each detector. We use the fact that bars can be re-oriented in the horizontal plane to maximize the overall sky coverage of the network. Fig. 3 shows clearly that, with a reorientation of the AURIGA and ALLEGRO axes (respectively by $\simeq +30$ *deg* and $\simeq -25$ *deg* from North to West), the detected amplitude is at worst one half of the gravitational wave amplitude for any source direction.

With bars at their SQL and interferometers at their predicted sensitivities, the network would extend the range of observations to the Virgo Cluster, according to predicted[?] burst source intensities.

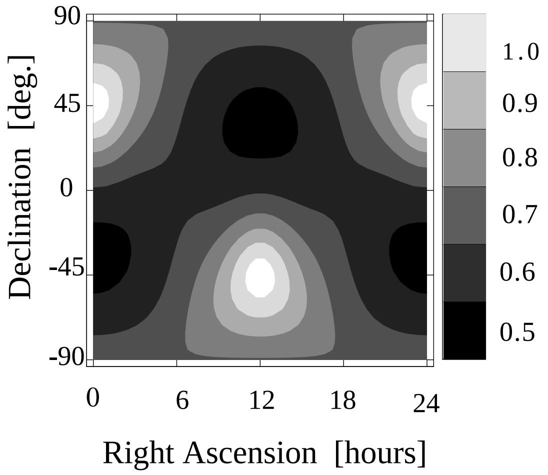

Figure 3. The sky coverage, averaged over polarizations, of a six detectors network (LIGO-LA, VIRGO, TAMA, GEO, AURIGA, ALLEGRO). The burst sensitivity is assumed to be the same for all the detectors. The gray scale on the right shows the amplitude sensitivity related to the maximal one: darker regions correspond to smaller amplitude sensitivities.

4. CONCLUSIONS

With the bar detectors presently in operation a Galatic supernova watch is becoming a reality. As soon as the transducers of the bar detectors are upgraded towards their SQL and the interferometers under construction start operation, such a watch for impulsive events (supervovae and final impacts of coalescing binary systems) will be gradually extended to the Local Group of galaxies and then to the VIRGO Cluster with event rate of at least few events per year.

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