

## First Search for Gravitational Wave Bursts with a Network of Detectors

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We report the initial results from a search for bursts of gravitational radiation by a network of five cryogenic resonant detectors during 1997 and 1998. This is the first significant search with more than two detectors observing simultaneously. No gravitational wave burst was detected. The false alarm rate was lower than 1 per  $10^4$  yr when three or more detectors were operating simultaneously. The typical threshold was  $H \approx 4 \times 10^{-21}$  Hz<sup>-1</sup> on the Fourier component at  $\sim 10^3$  Hz of the gravitational wave strain amplitude. New upper limits for amplitude and rate of gravitational wave bursts have been set.

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The direct detection of gravitational waves will be a watershed event for both the physics of gravitation and the investigation of compact astronomical objects. A variety of astrophysical events is expected to produce gravitational waves of short duration ( $\ll 1$  s), or *gw bursts*, such as the gravitational collapse of stars or the final few orbits and the subsequent coalescence of a close binary system of neutron stars (NS's) or black holes (BH's) [1]. Because of the inherent weakness of such signals, and the difficulty in distinguishing them from a myriad of noise sources, the direct detection of a gw burst will require coincident detection by multiple detectors with uncorrelated noise. Searches for gw bursts over periods of observation of 1–3 months have been performed in the past by pairs of cryogenic resonant bar detectors [2–4], setting upper limits on the incoming rate. A few days of observation have been reported for simultaneous operation of three cryogenic bar detectors [2] and, with much less sensitivity, of a pair of short-arm interferometric detectors [5]. Upper limits on gw signals from coalescing binaries have been recently reported also by a single interferometric detector for 25 hours of observation [6].

In the last few years, the increase of the number of cryogenic resonant detectors in simultaneous operation has greatly improved the prospects of obtaining a confident detection of gw bursts. There are now five operational cryogenic bar detectors: ALLEGRO (Baton Rouge, Louisiana, U.S.A.) [7], AURIGA (Legnaro, Italy) [8], EXPLORER (CERN) [9], NAUTILUS (Frascati, Italy) [10], and NIOBE (Perth, Australia) [11]. The groups operating these detectors agreed in 1997 to start a global search for short ( $\sim 1$  ms) gw bursts under common protocols, by establishing the International Gravitational Event Collaboration (IGEC) [12].

All these detectors use the same principles of operation. The gw excites the first longitudinal mode of the cylindrical bar, which is cooled to cryogenic temperatures to reduce the thermal noise and is isolated from seismic and acoustic disturbances. To measure the strain of the bar, a secondary mechanical resonator tuned to the cited mode is mounted on one bar face and a sensor measures the displacement between the secondary resonator and the bar face. The resulting noise of the detectors in terms of strain at the input is  $(5\text{--}10) \times 10^{-22}$  Hz<sup>-1/2</sup> in a bandwidth of  $\sim 1$  Hz

TABLE I. Main characteristics of the IGEC cryogenic bar detectors. The detectors measure the mean Fourier component  $H$  of the gw in the detection bandwidth of  $\sim 1$  Hz around the mode frequencies.  $H = (4L\nu^2)^{-1}\sqrt{E/M}$ , where  $E$  is the energy deposited in the bar by the gw and  $\nu$  is the mean of the mode frequencies. The bars are made by Al5056 except for NIOBE, whose bar is made of Nb. The sub-kelvin detectors and NIOBE showed very similar typical energy sensitivity in 1997–1998, better by a factor of about 4 with respect to the other detectors. The differences in mass and material, though, affect the gw sensitivity and give a conversion factor from  $\sqrt{E}$  to  $H$  which is 2.3 times worse for NIOBE than for the other detectors.

Detector	ALLEGRO	AURIGA	EXPLORER	NAUTILUS	NIOBE
Mode frequencies (Hz)	895,920	912,930	905,921	908,924	694,713
Bar mass $M$ (kg)	2296	2230	2270	2260	1500
Bar length $L$ (m)	3.0	2.9	3.0	3.0	2.75
Bar temperature (K)	4.2	0.2	2.6	0.1	5.0
Longitude	91°10'44"W	11°56'54"E	6°12'E	12°40'21"E	115°49'E
Latitude	30°27'45"N	45°21'12"N	46°27'N	41°49'26"N	31°56'S
Azimuth	40°W	44°E	39°E	44°E	0°

surrounding the two coupled-mode frequencies. Some of the important physical parameters of the five detectors are shown in Table I. The detector response is optimal for a gw incoming perpendicular to the bar axis and polarized along it [13]. The axes of all the bar detectors are aligned to within a few degrees of one another, so that the chance of coincidence detection is maximized. This makes the amplitude acceptance of the detectors for the Galactic center direction greater than 0.7 for about 60% of the time [14].

Each detector output is processed by filters optimized for short gw bursts, giving the estimate for the Fourier component  $H(\omega)$  of the strain amplitude  $h(t)$  in the detection bandwidth of  $\sim 1$  Hz around the mode frequencies listed in Table I. More specifically,  $h(t)$  is the gw amplitude multiplied by the antenna pattern of the detector [13]. With the exception of the ALLEGRO detector, the noise of the detectors was typically not stationary over long observation times and was affected by some unmodeled noise sources, whose correlation with common environmental noise sources was found to be weak [15]. Figure 1 shows the variability of the noise of each detector during 1997–1998, in terms of the Fourier component of the

gw corresponding to unity signal-to-noise ratio,  $H_{\text{rms}}$ . The detectors had quite similar noise levels, since the typical values of  $H_{\text{rms}}$  were all within a factor of 3.

We point out that this search for bursts is suitable for any transient gw which shows a nearly flat Fourier transform  $H(\omega)$  of its amplitude  $h(t)$  at the two resonant frequencies of each detector. The metric perturbation  $h(t)$  can either be a millisecond pulse, a signal made by a few millisecond cycles, or a signal sweeping in frequency through the detector resonances. The IGEC search is therefore sensitive to different kinds of gw sources such as a stellar gravitational collapse [1], the last stable orbits of an inspiraling NS or BH binary, its merging, and its final ringdown [16]. The computation of  $h$  from the measured Fourier component  $H$  requires a model for the signal shape. A conventionally chosen shape is a pulse lasting  $\sim 10^{-3}$  s [17]; in this case,  $H$  should be multiplied by  $\sim 10^3$  Hz to get the corresponding strain amplitude,  $h$ .

This Letter reports the results of the first coincidence search for gw bursts performed by the IGEC observatory. The observations covered most of 1997–1998, including 625.0 days with at least one detector in operation, 260.4 days with at least two detectors in simultaneous operation, 89.7 days with three detectors, and 15.5 days with four. This is the first search with significant observation time with more than two detectors. The duration of simultaneous operation would have been greater if it had been possible to operate these instruments with higher duty factors, which were typically  $\lesssim 50\%$  during this period with the exception of ALLEGRO. More details on the observatory, its data exchange protocol, and the exchanged data set can be found in Ref. [14].

The analysis of the data can be divided into two parts: a generation of candidate *event lists* for each of the individual detectors, and a time coincidence analysis using the lists. This approach, though not optimal, has the advantage of being easily implemented and provides for a satisfactory effectiveness.

Each IGEC group extracted the candidates for gw bursts, or *events*, by applying a threshold to the filtered output of

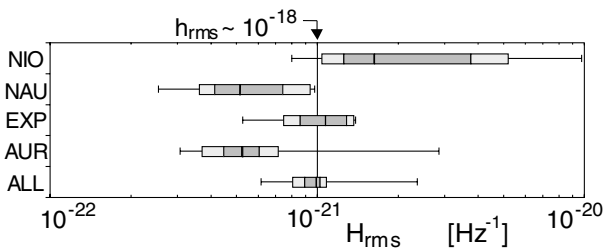


FIG. 1. Spread of the noise of detectors during 1997–1998 in terms of the Fourier component  $H_{\text{rms}}$  of the gw at  $\text{SNR} = 1$ . The plotted bands of variability of the noise are delimited by selected percentiles, i.e., by selected fractions of the observation time for which the sensitivity has been better than  $H_{\text{rms}}$ : innermost tick 50%, gray band 16%–84%, white band 2.5%–97.5%, and “T” lines 0%–100%. The corresponding gw amplitude  $h_{\text{rms}}$  for a  $\sim 10^{-3}$  s burst is sketched in the upper scale.

the detector. The events were described by their Fourier magnitude  $H$ , their arrival time, the detector noise at that time, and other auxiliary information. To limit the expected rate of accidental coincidences, each detector threshold was adaptively set to obtain a maximum event rate of  $\sim 100$  per day, with typical values in the range  $H_{\text{det}} \sim (2-6) \times 10^{-21} \text{ Hz}^{-1}$  corresponding to magnitude signal-to-noise ratio  $\text{SNR} \approx 3-5$ . Single spurious excitations are vetoed against disturbances detected by environmental sensors. The AURIGA detector checked each event against the expected waveform template by means of a  $\chi^2$  test [18]. The lists of the events exchanged within IGEC by each detector also include declarations of the off and on times for the detectors.

All searches for coincident events used a time window of 1.0 s. This choice limits the false dismissal probability to less than a few per cent while it ensures a very low false alarm probability when at least three detectors are observing simultaneously. No three- and fourfold coincidence was detected, and therefore we did not identify candidates for gravitational wave detection in the 89.7 days of threefold observation. The detector thresholds were typically  $3 \times 10^{-21} \text{ Hz}^{-1}$  for the most sensitive threefold configuration (ALLEGRO-AURIGA-NAUTILUS) and  $5 \times 10^{-21} \text{ Hz}^{-1}$  for the others. To give examples of detectable signals, these thresholds would correspond to, respectively,  $\sim 0.04 M_{\odot}$  and  $0.11 M_{\odot}$  converted to isotropic radiation in the optimal polarization at the distance of the Galactic center (10 kPc), assuming a gw burst of 1 ms duration [17]. For comparison, the signal expected from the last stable orbits of an optimally oriented NS coalescing binary at 10 kPc with  $2 \times 1.4 M_{\odot}$ , would give  $H(\omega) = (3-4) \times 10^{-21} \text{ Hz}^{-1}$  at the detector resonant frequencies. The number and amplitude of the twofold coincidences found in the 260.4 days of twofold observation are in agreement with the estimated accidental background [14].

The estimation of the false alarm rate is a crucial element in any gw search. It allows for the interpretation of any observed coincidences as well as the evaluation of the potential of the observatory. Since the events arrival times of each detector are randomly distributed with a nonstationary rate, the expected background of accidental coincidences can be computed by two methods: (i) by modeling the event times as Poisson point process and using the measured rates of events for each detector, and (ii) by counting the coincidences after performing even time shifts of the event times of one detector with respect to the others [2].

In the first approach, the expected rate of accidental coincidences is [19]

$$\lambda = N \frac{(\Delta t)^{N-1}}{T_{\text{obs}}^N} \prod_{i=1}^N n_i, \quad (1)$$

where  $N$  is the number of detectors simultaneously operating,  $T_{\text{obs}}$  their common observation time,  $\Delta t = 1$  s the

maximum time separation for a coincidence, and  $n_i$  the number of events of the  $i$ th detector during  $T_{\text{obs}}$ . This equation holds even if the event rates of detectors are not stationary as long as they are uncorrelated among different detectors.

The second approach is more empirical. In the case of the twofold coincidence searches, the time shift results are in agreement with those predicted through Eq. (1) [14], and demonstrate that the event rates of different detectors are uncorrelated.

The capabilities of the IGEC observatory with respect to the false alarm probability are shown in Fig. 2 for a few sample configurations of the observatory. The accidental rate is calculated as a function of a signal amplitude threshold  $H_{\text{thr}}$  at the detectors by applying Eq. (1) to the number of events of the detectors whose amplitude is  $\geq H_{\text{thr}}$ . The typical time variability of the instantaneous accidental rate  $\lambda$  has been calculated by means of a Monte Carlo simulation based on the measured nonstationary behavior of event rates on single detectors. This variability is about 1 order of magnitude with respect to the mean and is mainly determined by the nonstationary performances of the detectors. The estimated mean background of twofold coincidences is still fairly high, unless  $H_{\text{thr}}$  is raised well above the data exchange threshold  $H_{\text{det}}$ . On the other

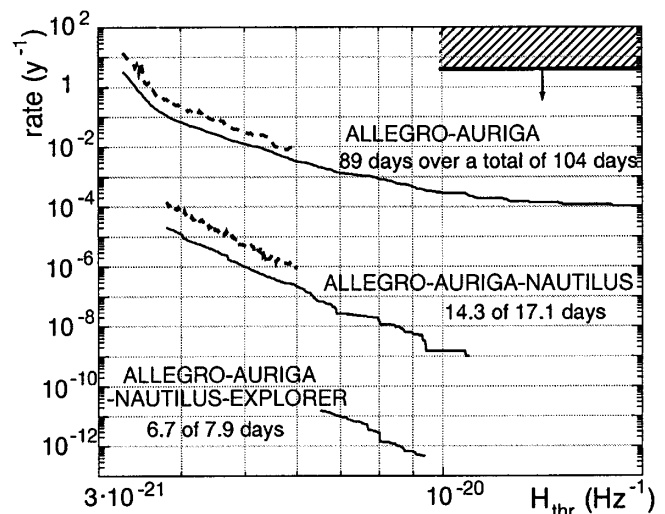


FIG. 2. Estimated rate of accidental coincidences,  $\lambda(\text{yr}^{-1})$ , versus the threshold  $H_{\text{thr}}(\text{Hz}^{-1})$  for a sample pair, triple, and four-tuple of detectors in 1997–1998. The continuous lines show the mean value of  $\lambda$  for signal amplitudes  $\geq H_{\text{thr}}$ . The dashed lines represent the 1 standard deviation upper bounds for the time variation of the instantaneous accidental rates. This figure takes into account the best 85% of common observation times, when every detector had an event search threshold lower than  $3.25$ ,  $3.8$ , and  $6.5 \times 10^{-21} \text{ Hz}^{-1}$ , respectively, for the pair, the triple, and the four-tuple. The  $\lambda$ 's for the other operative configurations of detectors were similar, allowing for a small increase of the corresponding  $H_{\text{thr}}$ , at most by a factor of 2. The bold horizontal line with arrow stands for the new upper limit set by all IGEC detectors on the rate of incoming gw bursts during 1997–1998.

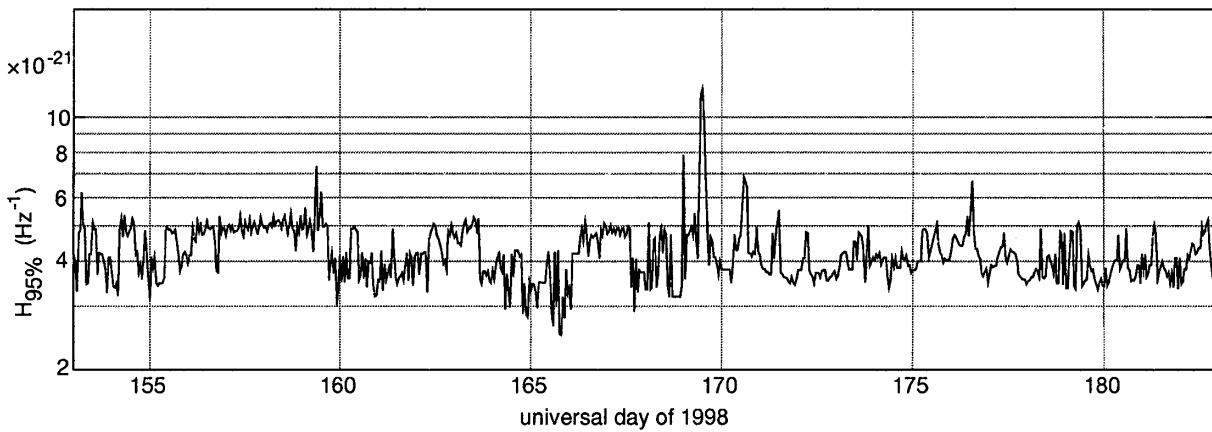


FIG. 3. A sample of the upper limit with 95% confidence on the amplitude of single gw bursts incident with optimal polarization and orientation on the IGEC observatory hour by hour in June 1998. The highest peaks shown are due to single high amplitude events of one detector while the others were not operating.

hand, a threefold or fourfold coincidence search keeps a high statistical significance even for  $H_{\text{thr}} \sim H_{\text{det}}$ , since the expected accidental rates are low enough: respectively, less than one false alarm per  $10^4$  or  $10^6$  yr of observation at  $H_{\text{thr}} \sim 4 \times 10^{-21} \text{ Hz}^{-1}$ . These fall rapidly as  $H_{\text{thr}}$  increases. In fact, the IGEC accidental background noise would remain negligible even after centuries of observation time.

The 260 days of observation with two or more detectors in simultaneous operation improved by about a factor of 3 the previously set upper limit on the rate of gw bursts incident on the Earth [3]. Assuming the emission is described by a stationary Poisson point process and using the same procedure as in Refs. [2,3], the limiting rate set for a gw burst emission from isotropically distributed sources is  $\leq 4 \text{ yr}^{-1}$  for  $H_{\text{gw}} \geq 10^{-20} \text{ Hz}^{-1}$  (Fig. 2) with 95% confidence. A more complete analysis is in progress.

The IGEC observatory can also be used to set an upper limit on the amplitude of gw bursts corresponding to astronomical events, such as supernovae or gamma ray bursts. For time windows of the order of the hour or larger, each detector is likely to show accidental events and therefore this upper limit benefits from a multiple coincidence search among the operating detectors.

A sample of the upper limits on the amplitude of gw bursts occurring within a time span of 1 h, is shown in Fig. 3 for a few weeks of 1998, when up to four detectors were operating. These limits apply to the component of the radiation emitted with optimal polarization from a source optimally oriented with respect to the detectors. We are 95% confident that there was no radiation above this level hour by hour. In all of 1998, the limits set by the IGEC observatory were better than  $H_{\text{gw}} = 6$  and  $4 \times 10^{-21} \text{ Hz}^{-1}$  for 94% and 21% of the year, respectively. To specialize these upper limits for a specific source direction, each detector response should be divided by its antenna pattern [13]. The corresponding observation times of the Galactic center by IGEC within the same limits have been, respec-

tively, 44% and 7.5% of 1998. For a source at the Galactic center emitting isotropically a 1 ms burst [17], the above upper limits correspond to about  $0.16M_{\odot}$  and  $0.07M_{\odot}$  converted in the optimal polarization.

Finally, we remark that the IGEC observatory is capable of monitoring the strongest galactic sources with a very low false alarm probability when at least three detectors are simultaneously operating. All the groups involved are actively working for upgrading the current detector performances and therefore we expect in the near future to extend the observation range to the Local Group of galaxies, which means an increase of a factor of 10 of the observed mass.

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