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Search for gravitational wave bursts by the network of resonant detectors

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Abstract

The groups operating cryogenic bar detectors of gravitational waves are performing a coordinated search for short signals within the International Gravitational Event Collaboration (IGEC). We review the most relevant aspects of the data analysis, based on a time-coincidence search among triggers from different detectors, and the properties of the data exchanged by each detector under a recently-upgraded agreement. The IGEC is currently analysing the observations from 1997 to 2000, when up to four detectors were operating simultaneously. 10% and 50% of this time period were covered by simultaneous observations, respectively, of at least three or at least two detectors. Typical signal search thresholds were in the range 2–6 10^{-21}/Hz. The coincidences found are within the estimated background, hence improved upper limits on incoming GW (gravitational wave) bursts have been set.

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1. Introduction

Resonant bar detectors are searching for gravitational waves with frequency components in the audio frequency range (700–900 Hz). Five have been operating in recent years, namely ALLEGRO [1], AURIGA [2], EXPLORER [3][18], NAUTILUS [4] and NIOBE [5] and have been aligned parallel to each other in order to maximize the chances of detection in coincidence. The International Gravitational Event Collaboration (IGEC) [6, 7], which gathers all the involved groups, is currently analysing observations from 1997–2000 to search for impulsive GW signals. Up to four detectors have been in simultaneous operation and preliminary results for 1997–1998 have already been reported [8]. The new analysis currently under way is still based on a time-coincidence search among candidate triggers provided by the single detectors, but it has been improved mainly on the assessment of the confidence level of the observations, in particular of false-alarm and false-dismissal probabilities. This required a wider set of information to be exchanged, together with a revision of the data exchange protocol [6] and of the data analysis methods [9]. In this paper we present the status of the current IGEC observatory. In particular, we report its duty cycle, sky coverage, sensitivity and partial results for the 1997–2000 observations. No statistically-significant evidence for a GW has been found. The extended IGEC observation improved the upper limits at Earth for GW bursts.

2. IGEC data analysis

The goal of the IGEC project is the search for transient gravitational wave signals, which show up frequency components in the wide range 700–900 Hz. Specifically, each detector output is filtered for impulsive (δ-like) signals before the candidates for GW detection, or *triggers*, are selected. Finally, a time-coincidence analysis of the trigger lists of the different detectors is performed. This kind of search is natural, since the resonant detectors are narrowband, and any transient signal with a nearly flat Fourier transform around the detector resonant frequencies

[18] From 1998, EXPLORER has been a CERN-recognized experiment.

is seen as δ-like. In fact, during 1997–2000, the typical frequency bandwidth of sensitivity of each detector was $\sim$1 Hz around its two mechanical resonant frequencies, which have been close to 700 Hz for NIOBE and about 900 Hz for the other detectors [8]. Even with improved bandwidths of $\sim$10 Hz, as demonstrated by EXPLORER from late 2000 and planned for most detectors in the near future, this framework will not change significantly. Examples of the wide class of GW signals monitored by IGEC are pulses of $\sim$1 ms duration, signals showing a few cycles of $\sim$1 ms period or sweeping in frequency across $\sim$1 kHz. The relevant amplitude information given by each detector is the estimate of the Fourier component $\boldsymbol{H}$ of the GW strain amplitude $\boldsymbol{h(t)}$ at the detector resonant frequencies. To get an estimate of the corresponding $\boldsymbol{h}$ amplitude, hypotheses on the signal template are required. For instance, $\boldsymbol{H}$ $\sim 3 \times 10^{-21}$/Hz can be related to either the inspiral phase of a coalescing NS–NS of $\sim 2 \times 1.4\ M_{\odot}$ at 10 kPc, or to a $\sim$1 ms burst of amplitude $\boldsymbol{h} \sim 6 \times 10^{-18}$. The latter would also correspond to $\sim 0.04\ M_{\odot}$, converted in isotropic GW radiation at 10 kPc.

The information requested by IGEC from each group includes both trigger parameters and detector operation parameters. The list has recently been revised [6]. The triggers are described by their amplitude and arrival time, i.e., the local maximum of the filtered output of the detector and its occurrence time. In addition, information about amplitude and timing uncertainties is exchanged by means of the variance and other higher-order central moments of the related random variable, as well as by estimates of systematic errors, such as those due to the amplitude calibration accuracy. The description of the detector operation includes the on/off times, the value of the amplitude threshold used to select the exchanged triggers and information about identified transient disturbances. The parameters related to the detector operation that do not depend on the trigger properties are exchanged periodically when their variation is significant, while the other parameters are given at each trigger.

The choice of the amplitude threshold for trigger selection at each detector is a compromise between two opposing requirements. On one hand, in order to maximize the sensitivity to GW detection, the search has to be pushed to low signal-to-noise ratios (SNR). However, for signals detected at extremely low SNR, the trigger amplitude is systematically overestimated and the uncertainty on the trigger time blows up [10]. The latter effect, combined with the sharp increase in the rate of background triggers, can give rise to an unreasonable false-alarm rate after the coincidence search. As for all aspects relating to the exchanged data sets, each partner group of IGEC is responsible for choosing a suitable detector threshold and providing the required information. In 1997–2000, the amplitude thresholds have been set between about SNR = 3 for ALLEGRO and NIOBE and SNR = 5 for AURIGA.

The multidetector data analysis consists of selecting the common observation time and performing a time-coincidence search among the related trigger lists. The common observation time can be selected as a function of a common search threshold on signal amplitude, i.e., by keeping the operating time of the detectors when their single thresholds are better than the common search threshold. As the detectors share almost the same directional sensitivity, a blind search irrespective of the source location is easily implemented. To improve the sensitivity for a specific direction in the sky, the antenna pattern factors can be accounted for. The time-coincidence analysis ensures a selected maximum false dismissal for the coincidence search due to the timing errors. This is accomplished by setting the width of the time window of each trigger to a multiple of the related standard deviation of the timing error, so that the desired confidence level of the interval is ensured by means of the Tchebicheff inequality, which is very conservative and works for any practical statistical distribution of time estimates. A coincidence is then issued when time windows of triggers of different detectors overlap. The analysis so far has been performed with a confidence level

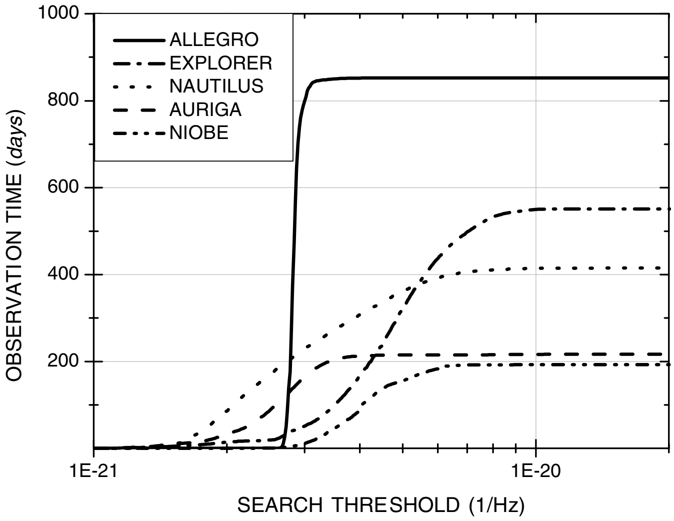

Figure 1. Observation time of IGEC detectors as a function of the signal search threshold for the period 1997–2000. For each detector, the ordinate is the integrated time during which the threshold set for trigger selection has been lower than the amplitude on the abscissa.

CL $\geqslant$ 0.95 for an *M*-fold coincidence, by setting each trigger error box to ensure, separately, a CL $\geqslant (0.95)^{1/M}$.

The estimate of the noise background—i.e. the false-alarm rate—of such a time-coincidence anlaysis with variable time windows can only be made by Monte Carlo methods. In particular, we implemented the empirical estimate obtained by averaging the observed coincidence rates over many time shifts on the exchanged data of one detector with respect to the others. Up to now, the analysis has computed up to a few million independent time shifts with a maximum delay of a few hours relative to the true time. Given that the maximum size of the time error boxes is of the order of the second, the minimum shift needed to realize an independent trial is a few seconds. The major issue on which we are working is the assessment of the accuracy of the method in our real case, where the non-stationary behaviour is evident over many time scales.

3. Observation time

During the period 1997–2000, each IGEC detector performed at least one scientific run, for a time span shorter than the entire four years, ranging from about 2.5 years for ALLEGRO to about 1 year for NIOBE. Within the run time, the effective observation time after validation has been a fraction, ranging from about 0.9 for ALLEGRO to 0.3 for AURIGA. Specifically, the cumulative operating time was 852.5 days for ALLEGRO, 551.0 for EXPLORER, 414.8 for NAUTILUS, 216.5 for AURIGA and 192.6 for NIOBE. The observation times of the detectors are shown in figure 1 as a function of the threshold on the GW signal amplitude; the graph indicates that typical performances of different detectors are spread within a factor of three. The ALLEGRO detector shows the most stationary behaviour, corresponding to a typical threshold of $\sim 3 \times 10^{-21}$/Hz. All others experienced wider changes in the detector sensitivity and threshold. The ultracryogenic detectors AURIGA and NAUTILUS have also

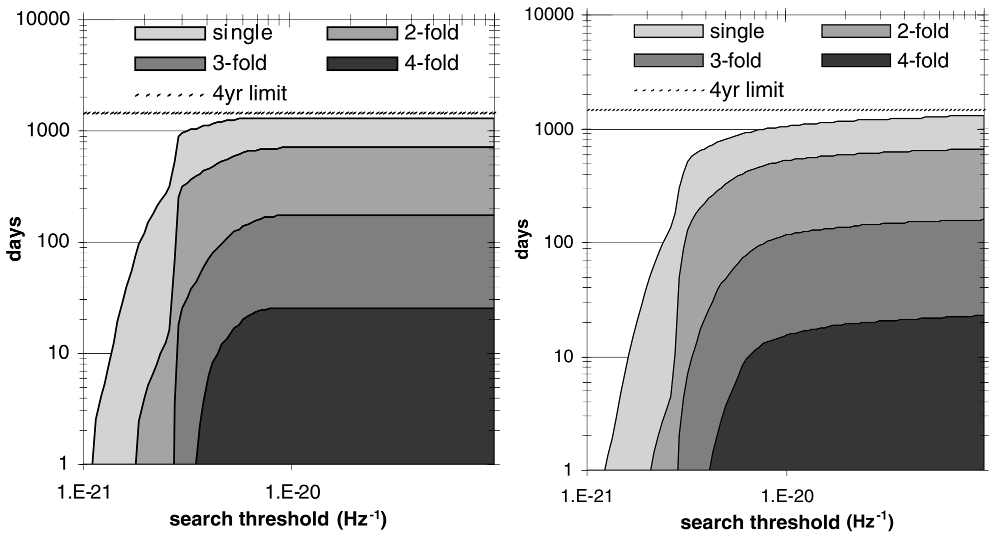

Figure 2. Cumulative observation time during 1997–2000 of the different configurations of the IGEC observatory versus the signal search threshold of the time-coincidence anlaysis. The abscissa refers to the GW signal component along the axes of the detectors (left) and to a signal coming from the Galactic Centre (right); both cases assume optimal polarization. The configurations of the observatory differ on the number of detectors in simultaneous observation (greyscale).

been effective at lower thresholds, while the cryogenic EXPLORER and NIOBE detectors were usually operating at higher thresholds.

The effectiveness of the sky coverage of a multidetector observatory is evident by looking at its cumulative observation time (see figure 2). During 1997–2000, four detectors were observing simultaneously for just a small fraction of the time span, of the order of 1%. A more significant coverage, of the order of 10%, has been achieved by the three-fold observations, which would still ensure a satisfactory confidence for independent signal detection due to their very low false-alarm probability. The observations by two detectors and by a single detector provided a much larger coverage, ∼50% and 90% of the four-year time span respectively; however, these configurations typically show higher false-alarm rates, but they are at least suitable for setting upper limits. These figures for the time coverage of the observatory are an obvious consequence of those obtained by the single detectors, which range from 13% to 58% of the entire time span. Of course, as the amplitude threshold for signal search is lowered, the useful observation time vanishes; in particular, the three-fold observations are no longer relevant for signal thresholds $<3 \times 10^{-21}$/Hz.

When searching for a GW signal from a specific direction of the sky, due to the antenna pattern of the detectors, all the exchanged parameters, which are linear to the amplitude (such as the trigger amplitude, its standard deviation and the threshold), increase by a factor $1/\sin^2(\theta)$, where θ is the angle between the bar axis and the GW direction. The resulting coverage of the Galactic Centre direction has been satisfactory, thanks to favourable antenna patterns (see figure 2). Of course, the observation time is fragmented due to the random superposition of the on/off times of the detectors, which are fragmented by themselves, as shown in figure 3. Moreover, three-fold, two-fold and single detector observations are, in general, not stationary because of switches among the contributing detectors.

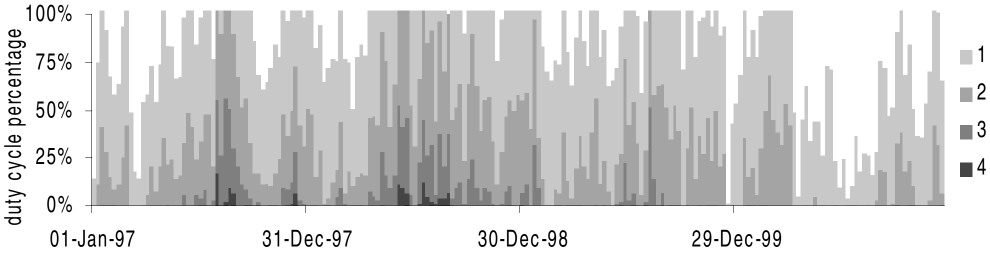

Figure 3. Weekly fraction of observation time for the four-fold, three-fold, two-fold and single detector configurations during 1997–2000 for an amplitude threshold of 6×10^{-21}/Hz from the Galactic Centre direction.

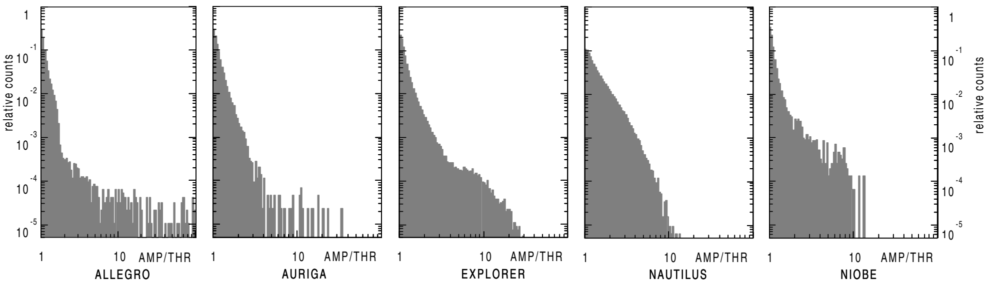

Figure 4. Amplitude histograms of the trigger exchanged by ALLEGRO, AURIGA, EXPLORER, NAUTILUS, NIOBE in 1997–2000, with the same log-binning of the abscissa. To compare the shapes of the trigger amplitude histograms of different detectors, the trigger amplitudes have been normalized to the related detector threshold, which were set respectively at SNR $\cong$ 3 for ALLEGRO and NIOBE, SNR $\cong$ 4.5 for EXPLORER and NAUTILUS and at SNR $\cong$ 5 for AURIGA. The ordinate shows the trigger counts normalized to the total number of triggers exchanged by the detector.

4. Triggers and time-coincidence results

The charateristics of the triggers exchanged by each detector within IGEC reflect the different behaviour of the single detectors. The amplitude histograms are shown in figure 4. The covered amplitude range is much wider than expected from a Gaussian model of the noise, indicating that additional noise sources always dominate at high SNR. The cleanest high-amplitude tail is shown by the detector AURIGA for two main reasons:

(i) its analysis implements a χ^2 test on the detected trigger shape to check its compliance with a δ-like GW excitation [12], enabling an effective rejection of spurious excitations in the amplitude range above SNR $= 10$ at the cost of a negligible additional false dismissal

(ii) the data validation includes statistical tests of the compliance of the measured noise with the model and with Gaussian statistics [13] at the cost of exchanging a smaller fraction of the operating time.

In general, the trigger lists exchanged for the current IGEC analysis differ from those previously exchanged for the 1997–1998 analysis [8] since EXPLORER, NAUTILUS and NIOBE have redefined their thresholds for trigger selection and the criteria used to determine the on/off times, resulting in a higher rate of exchanged triggers. During the 1997–2000 time span, the sensitivity performance of the detectors has been stable, apart from systematic improvements of a factor of two for AURIGA in 1999 and for EXPLORER in late 2000.

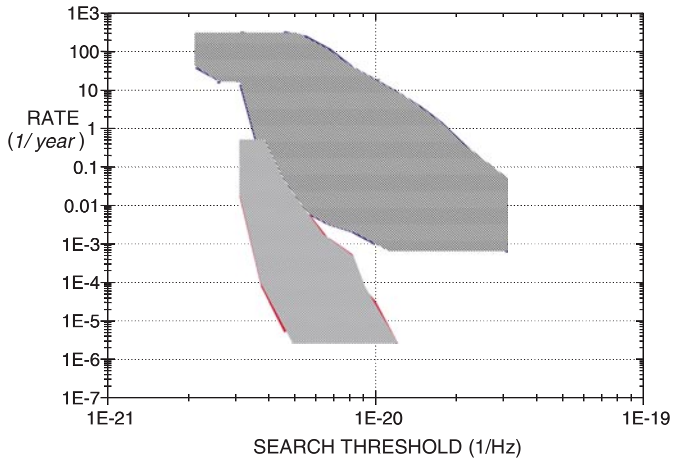

Figure 5. Predictions for the false-alarm rates of the IGEC observations in 1997–2000 as a function of the signal search threshold. All false-alarm rates for the triple configurations appear within the lower dashed region, while those related to detector pairs appear within the upper dashed region. The false-alarm refers to a time-coincidence anlaysis which ensures a CL $\geqslant 0.95$ of coincidences, includes the common observation time during which the detector thresholds were better than the search threshold and selects only the triggers with amplitudes greater than the search threshold. These predictions have been computed by means of the time-shift method.

These improvements, however, only slightly affect the overall performance of the observatory, since they have been obtained over a time span of much less than one year.

The maximum uncertainty of the trigger's arrival time is found at low SNR, near the detector threshold, where typical standard deviations range from 0.1 to 1 second [10, 11]. As the trigger SNR increases, the time uncertainty of each detector falls to levels given by systematic effects, which has been, at best, 1 ms for SNR > 20 for the detector AURIGA. This figure improves as the bandwidths of the detector widen. In any case, the current trigger time uncertainties do not allow us to resolve the light delay among detector sites, which range from 1 to 42 ms.

The estimates of the background of accidental coincidences obtained by applying the shift method support the preliminary results of the previous 1997–1998 analysis [8] (see figure 5). In the current analysis, the false-alarm estimates are relative to coincidences with CL $\geqslant 0.95$ and include all the common 1997–2000 observation times when the detector thresholds were lower than the signal search threshold on the abscissa. The three-fold configurations achieve a low false-alarm probability even close to the lowest common thresholds for signal search, and such probability falls rapidly as the signal search threshold is increased. The two-fold configurations instead show false-alarm rates which typically become much less than one over a year of observation time only for signals with high SNR. Work is in progress to test the accuracy of these false-alarm predictions.

The coincidences found at CL $\geqslant 0.95$ are within the expected background; in particular, no triple coincidence was found with the same selection described above for the observation time. Therefore, the current results improve the previous upper limits on the rate of GWs incident on Earth, mainly because of the extended observation time. The cumulative upper limit for incoming GWs is shown in figure 6. It has been computed from the total number of observed coincidences and related false alarms over the IGEC observation time, when at least two detectors were in simultaneous operation.

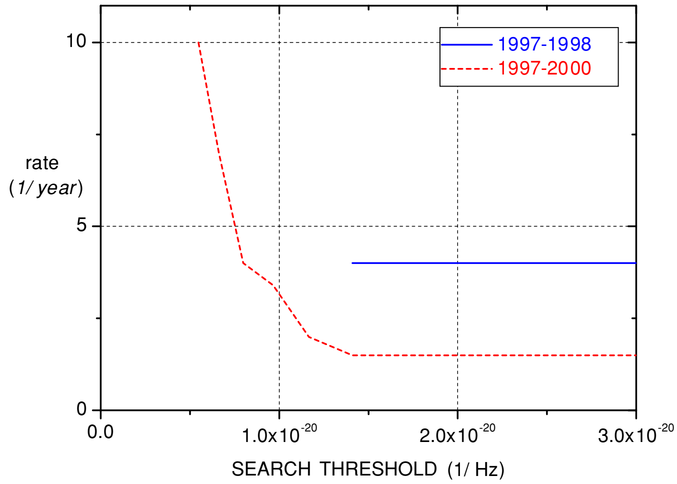

Figure 6. Upper limit on the rate of incoming GWs at CL = 0.95 as a function of the signal search threshold of the time-coincidence anlaysis. This limit is computed from the IGEC observations with at least two detectors in simultaneous operation and refers to the cumulative number of detectable GWs over the achieved observation time.

(This figure is in colour only in the electronic version)

5. Conclusions and final remarks

The data analysis of the IGEC observations from 1997–2000 is still in progress; no evidence for GW detection has been found and improved upper limits on the rate of incoming GW have been set at sensitivities useful for detecting galactic GW sources. The progress achieved in this analysis, with respect to the previous one, results mainly from the greater accuracy in assessing the false-alarm and false-dismissal probabilities of results and on the extended observation time.

Finally, let us point out two complementary aspects of the false-alarm estimates, as these are the predictions for the noise background of the observatory. On one hand, the results of any observation have to be compared with the false-alarm estimates under the same conditions, i.e. over the same actual observation time and with the same specific time-coincidence analysis. This comparison can either result in a claim for a detection or in an upper limit, once a CL has been set. On the other hand, one can predict the false-alarm probability for future observations, under the hypothesis of ergodicity, i.e., of long-term stability in the operation of the observatory. Basically, the observatory can improve its resolution on the GW rate estimates linearly with observation time as long as such a rate is much greater than the predicted false-alarm rate. Otherwise, the improvement will be weaker and proportional to the square root of the additional time. In particular, when setting upper limits, the latter regime is met when the expected number of false alarms is at least one. The current IGEC results indicate that, with a pair of detectors, the false alarms begin to show up after a short observation time, typically from days to years depending on the signal amplitude, while a triplet of detectors could observe for thousands of years before hitting any false-alarm, even at low SNR signals.

Another aspect relates to the basic and sub-optimal character of the IGEC analysis. This is due to the procedure of independent data reduction at each detector, including the setting of an amplitude threshold to select triggers before the multidetector analysis is performed. Instead, the optimal analysis would first make a weighted sum of the filtered outputs of the single detectors and then apply a single threshold on the resulting variable. A comparison between optimal and coincidence methods has been made in [14], but for wide-band detectors and for a different coincidence search method. In principle, the main disadvantage of the IGEC analysis is an overall lower efficiency in detection since more than one threshold has to be satisfied; on the other hand, its advantages are its simplicity and its much lower computing requirements. The achievable degree of detection efficiency is, in any case, not far from the optimal one. For example, for a triple configuration of detectors of similar sensitivity (a condition often met within IGEC) the false dismissal of a coincidence falls below about 5% for GW amplitudes which are two standard deviations greater than the single detector thresholds. The optimal method would instead achieve almost the same false dismissal for amplitudes one standard deviation greater than the single detector threshold. To determine how much this drawback in the efficiency affects the performance of a network of detectors, another fundamental issue has to be considered: the resulting false-alarm probability. This investigation, though, is much more difficult due to the fact that the false alarm depends crucially on the non-Gaussian tails of the detector noises. At this stage, we can only give indications based on the observed behaviour of the IGEC network. In the case where the goal of the analysis is to identify a single GW, the required false alarm should be negligible with respect to the reciprocal of the observation time. As a consequence, the detectable GW amplitudes are restricted to high SNR for any configuration made by a pair of detectors and only higher-multiplicity configurations can approach the actual single detector thresholds. The false-alarm requirements seem, therefore, to limit the effectiveness of any analysis method to an amplitude range such that the current IGEC analysis does not suffer significantly with respect to the optimal case. Instead, in the case where the goal of the analysis is to set upper limits, the requirement on the resulting false alarm is relaxed and therefore the cited limitation on detection efficiency for amplitudes close to the single detector thresholds would dominate the comparison of the analysis methods.

References

[1] Mauceli E *et al* 1997 *Phys. Rev.* D **54** 1264
[2] Prodi G A *et al* 1998 *Proc. 2nd Edoardo Amaldi Conf.* ed E Coccia *et al* (Singapore: World Scientific) pp 148–58
[3] Astone P *et al* 1993 *Phys. Rev.* D **47** 362
[4] Astone P *et al* 1997 *Astropart. Phys.* **7** 231
[5] Blair D G *et al* 1995 *Phys. Rev. Lett.* **74** 1908
[6] See http://igec.lnl.infn.it
[7] Prodi G A *et al* 2000 *Int. J. Mod. Phys.* D **9** 237
[8] Allen Z A *et al* 2000 *Phys. Rev. Lett.* **85** 5046
[9] Baggio L *et al* 2002 *Proc. of the 4th Edoardo Amaldi Conf. on Gravitational Waves (Perth, Western Australia, 8–13 July 2001) Class. Quantum Grav.* **19** 1541
[10] Ortolan A *et al* 2002 *Proc. of the 4th Edoardo Amaldi Conf. on Gravitational Waves (Perth, Western Australia, 8–13 July 2001) Class. Quantum Grav.* **19** 1457
[11] Astone P, D'Antonio S and Pizzella G 2000 *Phys. Rev.* D **62** 042001
[12] Baggio L *et al* 2000 *Phys. Rev.* D **61** 102001
[13] Prodi G A *et al* 2000 in *Proc. 3rd Amaldi Conf. (Caltech, CA, 1999)* ed S Meshkov (New York: AIP) p 345
[14] Finn L S 2001 *Phys. Rev.* D **63** 102001