STUDY OF COINCIDENCES BETWEEN RESONANT GRAVITATIONAL WAVE DETECTORS

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Abstract

Coincidences are searched with the cryogenic resonant gravitational wave detectors EXPLORER and NAUTILUS, during a period of about six months (2 June-14 December 1998) for a total measuring time of 94.5 days, with the purpose to study new algorithms of analysis, based on the physical characteristics of the detectors.

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1. Introduction

After the initial experiments with room temperature resonant detectors, the new generation of cryogenic gravitational wave (GW) antennas entered long term data taking operation in 1990 (EXPLORER [1]), in 1991 (ALLEGRO [2]), in 1993 (NIOBE [3]), in 1994 (NAUTILUS [4]) and in 1997 (AURIGA [5]).

Recently an analysis of the data taken in coincidence among all cryogenic resonant detectors in operation during the years 1997 and 1998 has been performed [6]. No coincidence excess was found above background using the event lists produced under the protocol of the International Gravitational Event Collaboration (IGEC), among the groups of ALLEGRO, AURIGA, EXPLORER / NAUTILUS and NIOBE. The coincidence search was done without any particular data selection. However one can consider the possibility to search for coincidences with events selected according to various possible criteria using all available information (we mention criteria based on: the event energy, the event duration, the applied threshold, the shape of the events, the coincidence window, the direction of possible GW, the noise).

Here we have used algorithms based on physical characteristics of the detectors, as the event energy (with a new algorithm) and the directionality. In this paper we explore their effect on the coincidence search.

For this purpose we shall use IGEC data obtained from 2 June 1998 when NAUTILUS, after a stop for instrumental improvements, resumed the operation. We search for coincidences between NAUTILUS and EXPLORER, whose apparatuses differ only in the operating temperatures (respectively 0.15 K and 2.6 K) and in particular have identical readout systems. Extension of the methods we develop here to other detectors in operation during the same period of time is envisaged.

Table 1: Main characteristics of the two detectors.

detector	latitude	longitude	orientation	mass kg	frequencies Hz	temperature K
EXPLORER	46.45 N	6.20 E	39^o E	2270	904.7 921.3	2.6
NAUTILUS	41.82 N	12.67 E	44^o E	2270	906.97 922.46	0.15

We are well aware that any data selection jeopardizes the possibility to express the results by means of a $probability$ that a coincidence excess, if any, had been accidental. With this $proviso$ we shall still use parameters obtained from probability estimations for comparing different situations.

2. Events and signals

We now briefly describe how we obtain $events$ from the measurements. For EXPLORER and NAUTILUS, whose main characteristics are given in table 1, the data are sampled at intervals of 4.54 ms and are filtered with a filter matched to short bursts [7] for the detection of delta-like signals. The filter makes use of power spectra obtained with off-line analysis. After the filtering of the raw-data, $events$ are extracted as follows. Be $x(t)$ the filtered output of the detector. This quantity is normalized, using the detector calibration, such that its square gives the energy innovation E of the oscillation for each sample, expressed in kelvin units. For well behaved noise due only to the thermal motion of the bar and to the electronic noise of the amplifier, the distribution of $x(t)$ is normal with zero mean. The variance (average value of the square of $x(t)$) is called $effective\ temperature$ and is indicated with T_{eff}. The distribution of $x(t)$ is

$$f(x) = \frac{1}{\sqrt{2\pi T_{eff}}} e^{-\frac{x^2}{2T_{eff}}} \tag{1}$$

For extracting $events$ we set a threshold in terms of a critical ratio defined by

$$CR = \frac{|x| - |\bar{x}|}{\sigma(|x|)} = \frac{\sqrt{SNR} - \sqrt{\frac{2}{\pi}}}{\sqrt{1 - \frac{2}{\pi}}} \tag{2}$$

where $\sigma(|x|)$ is the standard deviation of $|x|$ (the moving averages $|\bar{x}|$ are made over the preceeding ten minutes) and

$$SNR = \frac{E}{T_{eff}} \tag{3}$$

The threshold is set at CR=6 in order to obtain, in presence of thermal and electronic noise alone, about one hundred $events$ per day, as agreed among the partners of the IGEC. This threshold corresponds to an energy $E_t = 19.5\, T_{eff}$. When $|x|$ goes above the threshold, its time behaviour is considered until it goes below the threshold for more than ten seconds. The maximum amplitude and its occurrence time define the $event$.

In general the $event$ is due to a combination of a signal which, in absence of noise, has energy E_s (due to GW or other forces) and the noise. The theoretical probability to detect a signal with a given $SNR_s = \frac{E_s}{T_{eff}}$, in presence of a well behaved Gaussian noise, is calculated as follows. We put $y = (s+x)^2$ where $s \equiv \sqrt{SNR_s}$ is the signal we look for and x is the gaussian noise. We obtain easily [8]

$$probability(SNR_s) = \int_{SNR_t}^{\infty} \frac{1}{\sqrt{2\pi y}} e^{-\frac{(SNR_s + y)}{2}} cosh(\sqrt{y \cdot SNR_s}) dy \tag{4}$$

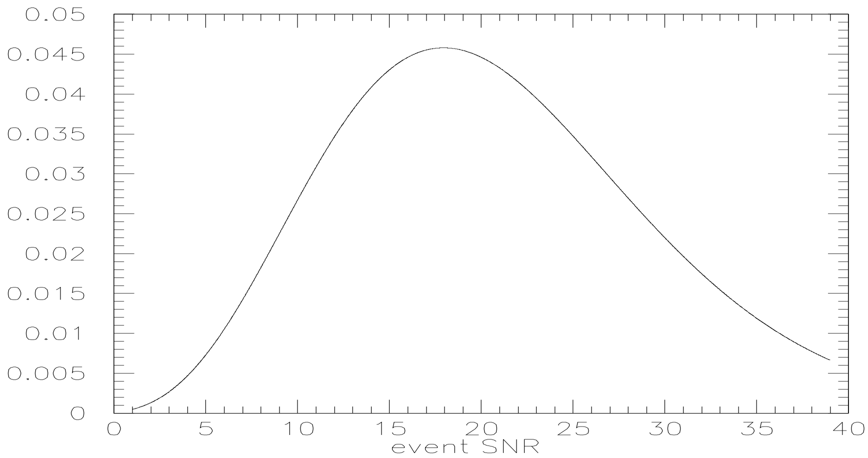

Fig. 1: Differential probability that the event has the signal-to-noise ratio shown on the abscissa when the signal has $SNR_s = 20$.

where we put $SNR_t = \frac{E_t}{T_{eff}} = 19.5$ for the present EXPLORER and NAUTILUS detectors.

The behaviour of the integrand is shown in fig. 1. This figure shows the spread of the event energy due to noise for a given SNR_s of the applied signal. The distinction between the two concepts, $signal$ and $event$, is essential for the analysis we propose in this paper.

3. Data selection

All the events which are in coincidence within a time window of $\pm 5\ s$ with events produced by a seismometer are eliminated, about 8% of the events.

It has been noticed that the experimental data are affected by noise which, in some cases, cannot be observed with any other auxiliary detector. Thus a strategy is needed for deciding when the measurements are considered to be good for the search of coincidences.

We are well aware that the selection of the experimental data must be done with great care and the safest strategy is to establish rules before even looking to the data. We have decided to take into consideration all the data recorded by the detectors (except those vetoed by the seismometer) and accept only the events for which the corresponding T_{eff} is below a certain threshold. This threshold must be such that we are confident that no signal is being thrown away. All and $only$ the events which have $T_{eff} \leq 100\, mK$ (over the preceeding ten minutes) are taken into consideration. The events for which the corresponding T_{eff} is greater than $100\ mK$ are certainly generated at times the detector is not operating properly.

The following information is available on the IGEC Web page for each event:
Time (UT) of the maximum of the event: YEAR, MONTH, DAY, MINUTE, SECOND.
H_o: Bilateral Fourier amplitude at resonance of the maximum.
SNR: Signal to noise ratio of amplitude.
T_{eff}: Effective temperature [K] of the previous 10 minutes.
Duration L of the event, in number of samples (4.54 ms).
Time in seconds between the beginning and the maximum of the event.

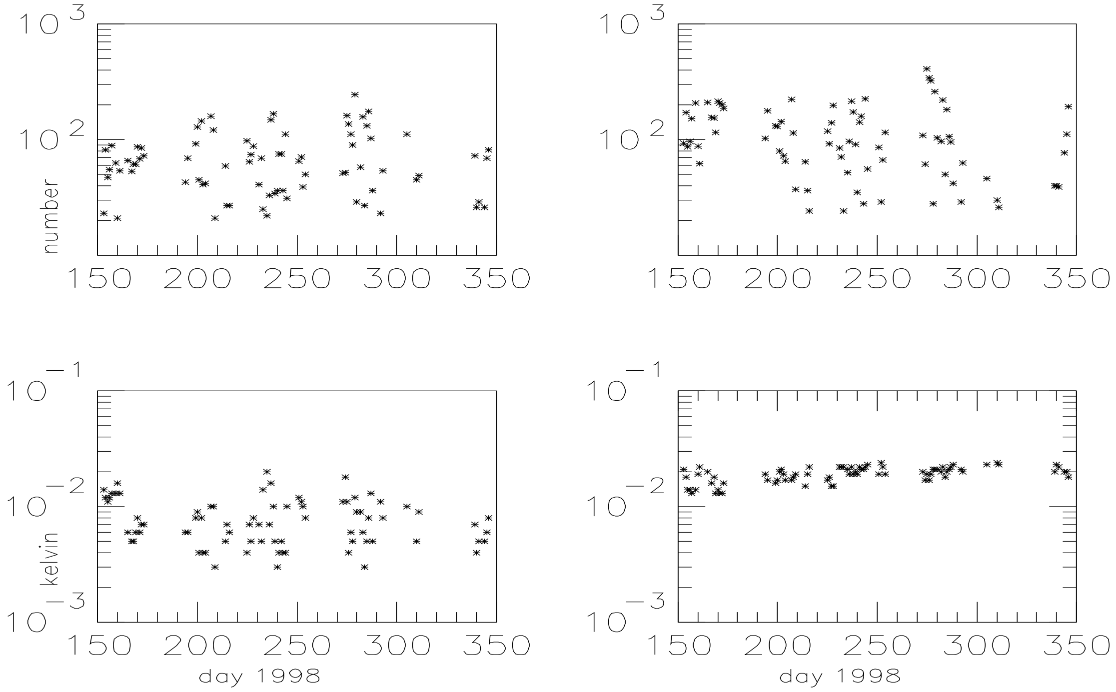

Fig. 2: $T_{eff} \leq 25\ mK$. The upper two figures show the number of events/day for NAUTILUS (left) and EXPLORER (right). The lower two figures show the noise temperature T_{eff} (kelvin) respectively for NAUTILUS and EXPLORER, daily averaged over the events.

The relationship between the Fourier transform H_o of the event amplitude and the energy E of the event is given by [9]

$$H_o = 7.97\ 10^{-21}\sqrt{E} \tag{5}$$

with H_o in units of $\frac{1}{Hz}$ and E in kelvin.

Looking to these events we have noticed that some events occur during periods of high disturbance. Since we are elaborating here strategies for data analysis, we have thought convenient to select the data to be used in our analysis in various ways according to the noise. Thus another way of choosing the data to be analysed is to select periods with smaller noise. We apply two more data selections, only events with $T_{eff} \leq 50\ mK$ for both EXPLORER and NAUTILUS and only events with $T_{eff} \leq 25\ mK$. This data selection has been applied by us in a previously published paper [10]. In fig.2 we show the number of events per day and the hourly averages of T_{eff} for EXPLORER and NAUTILUS for the case $T_{eff} \leq 25\ mK$.

We notice large fluctuations, in spite of the stringent criteria for the data selection. Information on the various data selections are given in table 2. We notice that the number of available hours of measurement becomes rather smaller when lowering the threshold for T_{eff}, so that any possible result becomes statistically weaker at low T_{eff}.

4. Searching for coincidences

For the search of coincidences it is important to establish the time window. We have decided to adopt the same window used in past analyses, in particular that described in papers [11, 6], $w = \pm 1\ s$. This is a reasonable choice considering the present detectors bandwidth (of the order of 1 Hz) and some time inaccuracy.

As well known, the analysis in a coincidence search consists essentially in comparing the detected coincidences at zero time delay with the background, that is with coincidences occurring by chance. In order to measure the background due to the accidental coincidences, using a procedure adopted since

Table 2: Total number N of events, number of hours of data taking, average noise temperature $< T_{eff} >$ and hours in common, when both detectors were simultaneously operating.

	T_{eff} mK	N	hours	$< T_{eff} >$ mK	hours in common	N
EXPLORER	≤ 100	55070	3415	40.6	2271	37944
NAUTILUS		37734	3450	19.1		24118
EXPLORER	≤ 50	39211	2759	28.9	1816	26481
NAUTILUS		34148	3371	14.0		16677
EXPLORER	≤ 25	16172	1498	18.7	931	9765
NAUTILUS		27823	3168	9.3		5999

Table 3: Number n_c of coincidences and average number $\bar{n}$ of accidentals. The total period of time in common when $T_{eff} \leq 100\ mK$ is 94.5 days.

T_{eff}	n_c	$\bar{n}$	hours
$\leq 100\ mK$	223	231.7	2271
$\leq 50\ mK$	137	139.8	1816
$\leq 25\ mK$	32	36.2	931

the beginning of the gravitational wave experiments [12], we have shifted the time of occurrence of the events of one of the two detectors 1,000 times in steps of 2 s, from -1,000 s to +1,000 s. For each time shift we get a number of coincidences. If the time shift is zero we get the number n_c of $real$ coincidences. The background is calculated from the average number of the n_{shift} accidental coincidences obtained from the one thousand time shifts

$$\bar{n} = \frac{\sum_1^{1000} n_{shift}}{1000} \tag{6}$$

With this experimental procedure for the evaluation of the background we circumvent the problems arising from a non very stationary distribution of the events, provided we test properly the distribution of the shifted coincidences (see fig. 4 and reference [13]).

The result of our search for coincidences is given in table 3. There is no coincidence excess between EXPLORER and NAUTILUS, even for selected periods with smaller noise.

5. Data selection using the event energy

We want now to apply data selection algorithms based on the event energy. The most obvious one is to search for pairs of events which have (approximately) the same energy. In the past this energy criterion has been applied, requiring that the responses of the EXPLORER detector at the two resonance modes were within a factor of two one from each other[1]. Later we realized that the effect of the noise on signals near threshold is such that the event energies are only lightly correlated to the signal energies [14], and this reduces the efficiency of algorithms based on the event energy.

Recently an important result was found [15]. It has been seen that the distribution of the energy ratios of the event energies of two detectors, in the case of non gaussian noise, is different for real coincidences and accidental coincidences. This has pushed us to reconsider the importance to apply selection algorithms based on the event energies.

For making use of the event energy, in particular with detectors with different sensitivity, we must consider the result shown in fig. 1 which indicates the chance to have a certain event-energy for a given signal-energy. In principle, all event-energies are possible, from zero to infinity. Our procedure here is to consider only event-energies within $\pm$ one sigma from the signal energy (that is, we consider events

Table 4: Energy algorithm. Number n_c of coincidences, average number $\bar{n}$ of accidentals and the covered time period for the three data selection.

T_{eff}	n_c	$\bar{n}$	hours
$\leq 100\ mK$	61	50.5	2271
$\leq 50\ mK$	45	37.7	1816
$\leq 25\ mK$	11	10.3	931

included in 68% of the area under the line in fig. 1).

We do not know the signal-energy. The new algorithm we propose is the following. We consider signals in a wide range, say: E_s from 20 mK to 2 K in steps of 20 mK. We find the coincident events, at zero delay (the real coincidences) and at shifted times (for the estimation of the accidentals). For each assumed signal with energy E_s we calculate the SNR_s different for each event, since the noise T_{eff} depends on the detected event and it is also different for the two detectors. We then verify if the SNR_{event} falls into $SNR_s \pm 1\ sigma$, having calculated for each SNR_s the probability curve like that shown in fig. 1 for $SNR_s = 20$. If the two event energies are compatible with the event-energy expected for any of the assumed signals then we accept the coincidence (real or shifted).

The result of this analysis is given in table 4. We notice that the use of the energy selection algorithm has reduced the number of the accidental coincidences by a factor of three.

6. Event selection according to the detector orientation with respect to the Galactic Centre

No extragalactic GW signals should be detected with the present detectors. Therefore we shall focus our attention on possible sources located in the Galaxy. If any of these sources exist we should expect a more favorable condition of detection when the detectors are oriented with their axes perpendicular to the direction toward the Galactic Centre (GC), since, the bar cross-section is proportional to $sin^4(\theta)$, where θ is the angle between the detector axis and the direction to the GC.

After having applied the above energy algorithm, we search for coincidences considering only events obtained when the detectors were oriented with θ greater than various given values and, according to the previous sections, for the various data selection.

The result is given in fig.3 and shows a larger coincidence excess when the detector axes tend to be perpendicular to the direction towards the GC. Above $\theta \sim 79^o$ the number n_c of coincidences drops quickly. If not instrumental, the quick drop could be taken as due to the width of the source. The time spent by the detectors when $\theta \geq 79^o$ is 20% of the total time of 94.5 days.

We want now to verify that the evaluation of the background is properly done. We do this in the condition of the greatest coincidence excess, that is for $\theta \geq 79^o$. We must consider that by selecting only times when the detectors had certain orientations we have several empty time regions. This makes it possible that in doing the shifting operation for evaluating the background one uses time periods of different duration. We have determined these time periods and found that they vary by a few percent, with a maximum of -10% for a time shift of +1000 s. In fig. 4 we show, for the case $\theta \geq 79^o$ and $T_{eff} \leq 100\ mK$, the delay histogram with no correction and the delay histogram corrected for the different periods of time for each shift. In this particular case the correction applies for a very small amount only for delays greater than about 700 s.

7. Conclusions

In order to make a first step to a complete analysis, we have selected the IGEC events of EXPLORER and NAUTILUS using algorithms based on known physical characteristics of the detectors. In particular a new algorithm which makes use of the event energy has been devised.

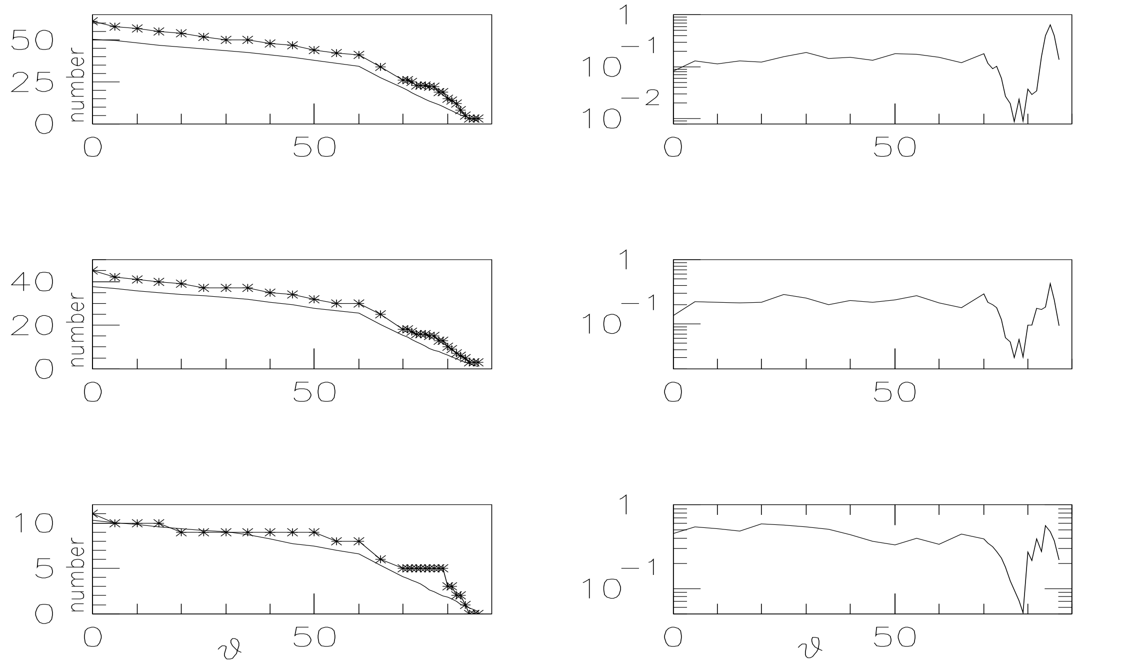

Fig. 3: The upper left figure shows, versus θ and for $T_{eff} \leq 100\ mK$, the integral number of coincidences n_c (indicated with asterisks) and the average number of accidentals $\bar{n}$ (calculated from the number of coincidences at zero delay and the average background $\bar{n}$ measured with 1000 delays). The right figure shows the Poisson probability that the observed number of coincidences n_c was due to a background fluctuation. Similarly the second line of figures refers to the data selection $T_{eff} \leq 50\ mK$ and the third line to the data selection $T_{eff} \leq 25\ mK$.

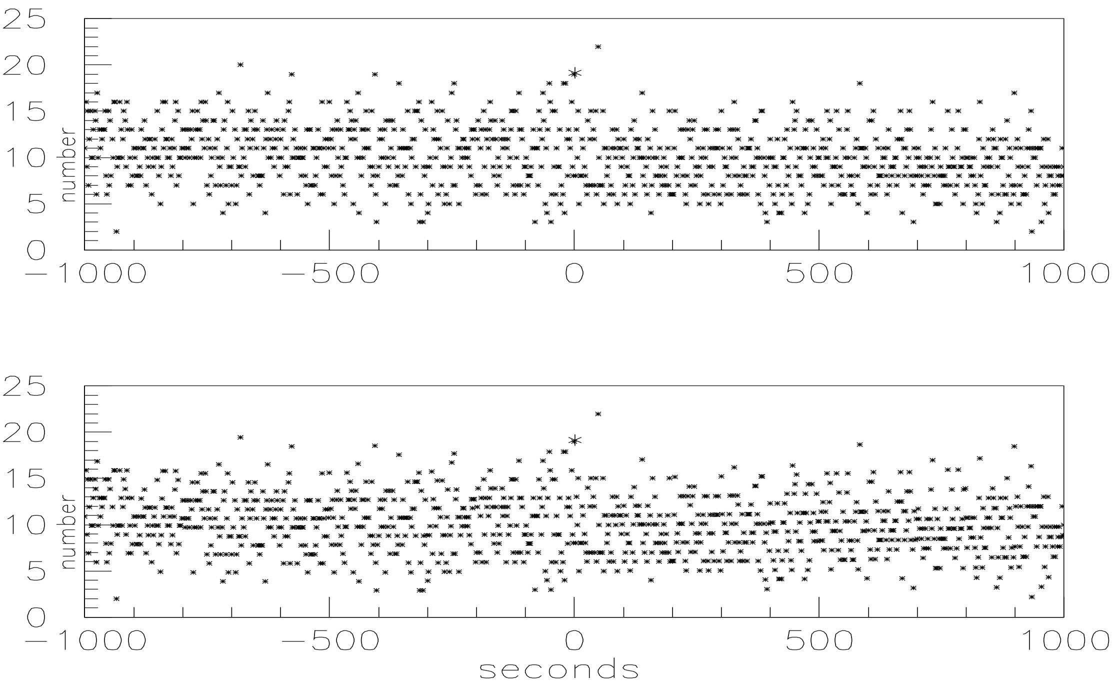

Fig. 4: Data selection with $T_{eff} \leq 100\ mK$. In the upper figure we show, for $\theta \geq 79^o$, the delay histogram. In the lower figure we show the same data normalized for the duration of the time period used for each time shift. In this particular case the normalization turns out to be very small, almost barely visible for delays above 700 s, but it is worth to remark that a possible effect due to different time coverage at various delays has been taken into account. The biggest asterisk indicate the nineteen coincidences at zero time delay.

With event selection based on this algorithm we find an excess of coincidences at zero time delay in the direction of the Galactic Centre. As well known in the scientific community, no g.w. signals are expected to be observed with the present detector sensitivity. Since this result would open new possibilities, a careful Bayesan approach suggests that, given the Poisson probabilities of a few percent, new data with other detectors are required before we can ensure that g.w. from the GC have been indeed observed. Thus, at present, we feel that the coincidence excess is not large enough to establish a claim for detection of true signals, but it is an important information to make available to the scientific community. We believe that the procedures adopted here might be useful for detecting gravitational waves with more or better data.

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References

[1] P. Astone et al., Phys. Rev. D. **47**, 362 (1993).

[2] E. Mauceli et al., Phys.Rev. D, **54**, 1264 (1996)

[3] D.G. Blair et al. Phys. Rev. Lett.**74**, 1908 (1995).

[4] P. Astone et al, Astroparticle Physics,**7**, 231(1997)

[5] M.Cerdonio et al., First Edoardo Amaldi Conference on Gravitational wave Experiments, Frascati, 14-17 June 1994

[6] ”Initial operation of the IGEC Collaboration” G.A. Prodi, I.S. Heng, Z.A. Allen ,P. Astone et al. Submitted to 4th Gravitational Wave Data Analysis Workshop (GWDAW 99), Rome, Italy, 2-4 Dec 1999. Submitted to Int.J.Mod.Phys.D e-Print Archive: astro-ph/0003106

[7] P.Astone, C.Buttiglione,S.Frasca, G.V.Pallottino, G.Pizzella Il Nuovo Cimento **20**, 9 (1997)

[8] A.Papoulis ”Probability, Random Variables and Stochastic Processes”, McGraw-Hill Book Company (1965), pag 126.

[9] P.Astone et al, in ”Gravitational Astronomy” Ed. D.E.McClelland and H.A.Bachor, World Scientific (1990).

[10] P.Astone et al. Astroparticle Phys. **10**, 83 (1999)

[11] P.Astone et al. Phys.Rev. D, **59**, 122001 (1999)

[12] J. Weber, Phys. Rev. Lett. **22**, 1320 (1969).

[13] ”Background estimation in a gravitational wave experiment” P.Astone, S.Frasca, G.Pizzella ,Dec 1999. 6pp. Submitted to 4th Gravitational Wave Data Analysis Workshop (GWDAW 99), Rome, Italy, 2-4 Dec 1999. Submitted to Int.J.Mod.Phys.D e-Print Archive: gr-qc/0002004

[14] P.Astone, G.V.Pallottino, G.Pizzella, Journal of General Relativity and Gravitation, **30**, 105 (1998)

[15] D.Blair, P.Bonifazi et al., Journal of General Relativity and Gravitation, in press (2000).