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The 2003 run of the EXPLORER–NAUTILUS gravitational wave experiment

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Abstract

We report here the preliminary results of the search for gravitational wave bursts from the 2003 run of the EXPLORER–NAUTILUS experiment. The total common measuring time was 149 days. The detectors had a typical noise spectral amplitude of about 2×10^{-21} $\text{Hz}^{-1/2}$, a bandwidth of the order of 10 Hz and a very good stability. We derive a new upper limit for the GW burst rate, of the order of 0.02 events/day for $h_{\text{RSS}} \geqslant 2 \times 10^{-19}$, and discuss the implication of this result with respect to the results obtained with the 2001 run.

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1. Introduction

Several investigations for short gravitational wave (GW) bursts with modern detectors have been performed in the last few years setting upper limits on the incoming rate [1–6]. In 2002 the ROG collaboration presented the results of a search for GW bursts with the EXPLORER and NAUTILUS cryogenic bar detectors operating for nine months in the year 2001 [7]. The EXPLORER–NAUTILUS 2001 search had three important features: first, both detectors were operating at an unprecedented sensitivity; second, it introduced in the analysis a selection based on the energy compatibility of the events, already tested in the previous 1998 run [8] and third, a sidereal time analysis was performed in order to look for specific galactic signatures. A small excess of events with respect to the expected background was found, concentrated around sidereal hour 4. At this sidereal hour the two bars are oriented perpendicularly to the galactic plane, and therefore their sensitivity for galactic sources of GW is maximal. This observation has been debated in the literature and international workshops [9–11], and in spite of different evaluations of its statistical significance, the general opinion was that further experimental work was necessary to understand the presence and the meaning of the observed coincidence excess, and possibly to put the indications on a firmer ground. After an upgrade of the detectors, new data of EXPLORER and NAUTILUS are now available from the 2003 run. We present here the preliminary results of the analysis of these new data, using the same procedures applied to the 2001 run. Some results were finalized after the Amaldi 6 conference.

2. The detectors

GW detectors NAUTILUS, operating at the INFN Frascati Laboratory, and EXPLORER, operating at CERN, both consist of an aluminium cylindrical bar having a mass of 2.3 tons. The principle of operation of these detectors is based on the idea that the GW excites the first longitudinal mode of the 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 capacitive resonant transducer, tuned to the cited mode, is mounted on one bar face, followed by a very low noise superconducting amplifier.

The data are filtered with an adaptive filter matched to delta-like signals for the detection of short bursts [12]. This search for bursts is suitable for any transient GW which shows a nearly flat Fourier spectrum at the two resonant frequencies of each detector.

Let $x(t)$ be the filtered output of the detector. This quantity is normalized, using the detector calibration, such that its square gives the energy innovation of the oscillation for each sample, expressed in Kelvin units, and the same units are used for all the energies throughout the paper.

For well-behaved noise due only to the thermal motion of the oscillators and to the electronic noise of the amplifier, the distribution of $x(t)$ is normal with zero mean. Its variance (average value of the square of $x(t)$) is called *effective temperature* and is indicated with $T_{\rm eff}$. In order to extract from the filtered data sequence *events* to be analysed we set a threshold for $x(t)$ in terms of the critical ratio CR defined as

$$\mathrm{CR} = \frac{|x| - \overline{|x|}}{\sigma(|x|)}, \tag{1}$$

where $\sigma(|x|)$ and $\overline{|x|}$ are the standard deviation and the moving average of $|x|$, respectively computed over the preceding 10 min. The threshold is set at $\mathrm{CR} = 6$ in order to obtain a reasonable rate of events to analyse (see [8]). When $x(t)$ goes above the threshold, its time behaviour is considered until it falls back below the threshold for longer than 1 s. The maximum value E_e of x^2 and its occurrence time define the *event*. In the presence of a GW signal, E_e results from the combination of the energy E_s that a signal would impart to the noise-free detector initially at rest and of the noise.

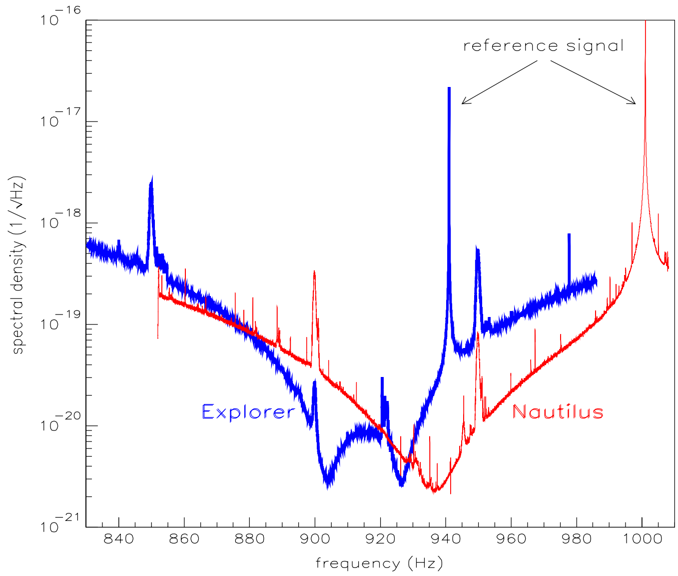

Figure 1. Typical sensitivity curve for EXPLORER and NAUTILUS detectors during the 2003 run.

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

The signal energy E_s is determined by the value of the Fourier transform $H(f)$ of the GW in the detector frequency band, giving, for optimal orientation:

$$H = \frac{L}{v_s^2}\sqrt{\frac{kE_s}{M}}, \tag{2}$$

where $v_s = 5400$ m s^{-1} is the sound velocity in aluminium, L and M are the length and the mass of the bar and k is the Boltzmann constant. Computation of the GW strain amplitude h from the energy signal E_s requires a model for the signal shape. Conventionally, in the bar community we are used to consider a short pulse having flat spectrum over the resonances region and an equivalent bandwidth $\Delta\nu$, resulting in the relationship:

$$h = H\Delta\nu, \tag{3}$$

where $\Delta\nu$ is assumed to be 1 kHz (for instance, for $E_s = 10$ mK we have $h = 8 \times 10^{-19}$ which requires a total conversion into GW of about 10^{-3} solar masses at the Galactic Centre).

With respect to the 2001 run, in the 2003 run NAUTILUS was equipped with a new transducer [13], very similar to that already operating on EXPLORER since 1999, providing a bandwidth of the order of 10 Hz, considerably larger than the previous one, resulting in a smaller time uncertainty of the events. Moreover, in 2003 also EXPLORER has been equipped, like NAUTILUS, with a cosmic ray detector. The main features of the two detectors are given in table 1, and their typical strain sensitivities in 2003 are shown in figure 1.

The sensitivity of the detectors to short GW bursts is well represented by T_{eff}, whose median values are reported in table 2.

3. Data analysis

Following the lines of our previous burst search [7], we applied *a priori* selection criteria to the time periods of each detector and to the events, selecting those with critical ratio CR $\geqslant 6$.

Table 1. Main characteristics of the two detectors in the year 2003. The bandwidths are the average values measured over the entire period of analysis.

Detector	Latitude	Longitude	Azimuth	Mass (kg)	Freq. (Hz)	Temp. (K)	Band (Hz)
EXPLORER	46.23 N	6.05 E	39° E	2270	904.7 921.3	4	8.7
NAUTILUS	41.82 N	12.67 E	44° E	2220	926.3 941.5	4	9.6

Table 2. Year 2003. Hours of common operation, number of events and median values of T_{eff} in mK.

	Explorer		Nautilus	
Common hours of operation	Events	T_{eff}	Events	T_{eff}
3569	72 086	2.1	114 911	3.6

Along the same lines, further selection criteria were then applied to the coincidence search, regarding:

(1) the time periods, selecting those with an hourly average noise level below a chosen value. We consider only time periods when the hourly average is $\langle T_{\text{eff}}\rangle_h \leqslant 6$ mK. The motivation for a selection in $\langle T_{\text{eff}}\rangle_h$ relies on the experimental evidence that the rate of accidentals increases with this parameter, while the detection efficiency of true signal should decrease;
(2) the T_{eff} associated with each event. We discarded all events with the preceding 10 min average $T_{\text{eff}} > 8$ mK;
(3) the SNR threshold. We have used the same threshold as for 2001 data, i.e. $\text{SNR}_e \geqslant 19.5$ (corresponding to $CR \geqslant 6$ for a Gaussian noise). We recall that this is the ratio between the energy E_e of the event and the T_{eff} associated with it;
(4) the time window used to define the coincidence. The time window used in the 2003 run analysis is fixed at 30 ms.

Let us discuss in detail this last criterion.

In the 2001 data, we assumed that the arrival time experimentally assigned to each event had a Gaussian distribution around the true signal time, with variance obtained by simulation [7]:

$$\sigma_t = \frac{0.28}{\Delta f}\sqrt{\frac{1}{\text{SNR}_e}}, \tag{4}$$

where Δf is the bandwidth of the detector (see table 1). For signals close to the threshold ($\text{SNR}_e = 19.5$) equation (4) gave $\sigma_t \simeq 7$ ms.

Afterwards, we modified our software, correcting some inaccuracies that caused the time resolution to be limited to few milliseconds. This was irrelevant in 2001 data, where the bandwidth of Nautilus was a fraction of a Hertz (leading to much bigger time uncertainties) while it became of the same order of magnitude as the achievable accuracy in 2003. We decided to experimentally determine the best time coincidence window to be applied. We could do that taking advantage of the fact that now the two antennas are equipped with a cosmic ray detector, allowing us to measure, both for Explorer and Nautilus, the time difference between the signal from the cosmic ray apparatus and the one from the antenna response. This measurement is important and is worth a brief description. The arrival of cosmic rays in the massive detector

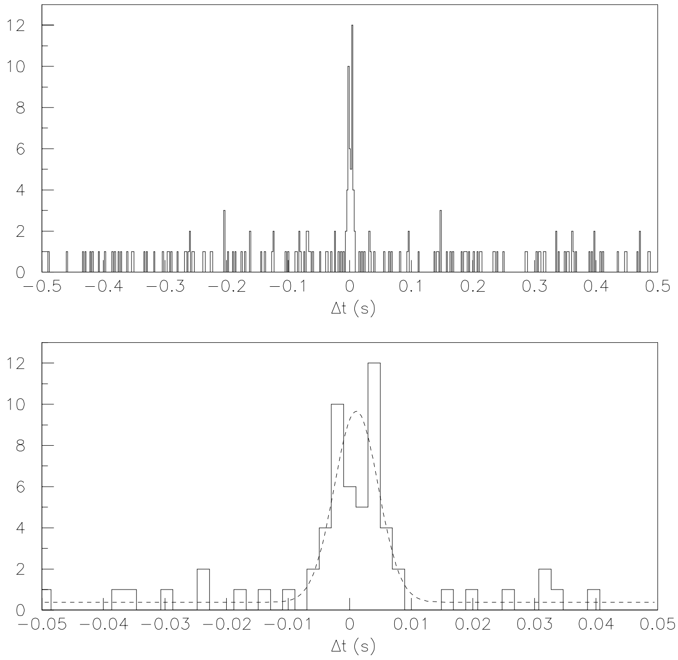

Figure 2. The distribution of the observed delays between the signal of the cosmic ray showers and the corresponding EXPLORER events. The distribution can be fitted with a constant (accidentals) plus a Gaussian, giving $\sigma = 3.6 \pm 0.5$ ms. The lower graph is a zoom of the upper one.

generates mechanical vibrations. The vibrations originate from the local thermal expansion caused by the warming up due to the energy lost by the particles crossing the material.

The measurements of cosmic ray showers made with our GW detectors ensure us that the detectors are indeed able to observe extremely small excitations of the bar longitudinal mode of vibration and they represent, in a way, a sort of calibration of the experimental apparatus and of the algorithms used for extracting small impulsive signals from the noise [14–16].

Here we are only interested in measuring the time dispersion between the arrival of the cosmic ray shower, which we know with great accuracy (<1 μs), and the event time obtained after the data filtering. Using the EXPLORER data we search for coincidences between the filtered data and the response of the cosmic ray apparatus. This consists of 15 plastic scintillators located on the top of the cryostat and 12 plastic scintillators located under the cryostat.

We note that the number of coincidences is much greater than the number of accidentals, so we can exclude that most of the observed coincidences are due to chance.

As shown in figure 2 we estimated the time uncertainty for the cosmic ray showers to be $\sigma_t \simeq 3.6 \pm 0.5$ ms, better than the 7 ms estimate from equation (4) and the previous experimental results obtained with the old software version.

However, we realized that the experimental time distributions are not really Gaussian, exhibiting much higher tails especially for events at low SNR ratio. Combining the uncertainties for the two detectors, and taking into account the 2.3 ms time required for GW to cover the distance of 700 km from EXPLORER to NAUTILUS at the speed of light, we evaluated that, in order to keep $\geqslant$99% of the possible coincidences (as we did in 2001 with the choice of $\pm 3\sigma$), the time window to be used is $\simeq \pm 30$ ms.

In the analysis reported here, the energy filter is not applied. The results of the application of this filter are very sensitive to the uncertainty on the detectors, calibration. As reported in section 2, NAUTILUS was equipped with a new transducer, and its operating characteristics are now quite different from the past and from EXPLORER ones, as one can clearly see from figure 1. As a consequence, we are not yet confident of knowing the relative calibrations of the detectors at the usual level ($\simeq$10%) of accuracy needed to apply in a consistent way the energy filter. Further detailed analysis and measurements are in progress trying to reduce the uncertainty in energy calibration, also taking advantage of the events generated by cosmic ray showers.

4. Experimental results

The common time of operation for EXPLORER and NAUTILUS begins on 27 March 2003 and ends on 12 December 2003. The total number of common hours, after the application of the various selections described in the previous section, is 3569 (148.7 days).

The coincidence search, with the previously described selections (hourly $\langle T_{\rm eff}\rangle_h \leqslant 6$ mK, $\mathrm{SNR}_e \geqslant 19.5$, coincidence time window = 30 ms), gave the following results: $n_c = 24$ coincidences and an average number of accidentals $\bar{n}_a = 18.8 \pm 0.2$ (18 804 counts over 1000 shifts).

The average number of accidentals has been obtained by time shifting one of the two event lists with respect to the other one, as in [7]. This average number compares well with the value estimated theoretically from the number of events. Furthermore, we verified that the distribution of the number of accidental coincidences for each time shift is Poissonian to a good accuracy.

We can see that, as already happened in 2001, the total excess of the number of coincidences n_c with respect to the average number of accidentals $\bar{n}_a$ is small. The corresponding Poissonian probability is in fact:

$$P(n \geqslant n_c, \mu = \bar{n}_a) = 0.14.$$

As has been pointed out in several papers [17–21], the sidereal time analysis has the potentiality to enhance the sensitivity of a coincidence experiment: indeed, while the accidentals should be insensitive to this parameter, the GW events could have a distinctive distribution due to the source distribution in space.

For the calculation of the sidereal hour we used here the Greenwich Mean Sidereal Time (GMST), while in 2001 we used the local sidereal time of longitude 9.46° (average between EXPLORER and NAUTILUS) which is $\simeq$0.63 h ahead of GMST. The obtained distributions are shown in figure 3, together with those against solar hour, both binned in 1 h bins. The number of accidental coincidences is estimated by shifting the data stream of one detector with respect to the data stream of the other by 1000 steps of 2 s and measuring the average number of coincidences in each 1 h bin.

In figure 4 we report how coincidences and accidentals were distributed along the year, binned in 10 days as a function of the day of the year. In figure 5, the integral difference between coincidences and accidentals is shown as a function of the running time.

The average rate of excess is about 1 every 30 days.

One can note that most of the coincidences' excess is concentrated in the period of days 320–330 (November 16–26), where there are 5 coincidences against a background of 0.93. A similar clustering in the coincidences' excess was already noted in the 1998 data: this is why we decided to look at the time distribution of coincidences and started to study its statistics, also in the light of the arguments illustrated at the beginning of the following section.

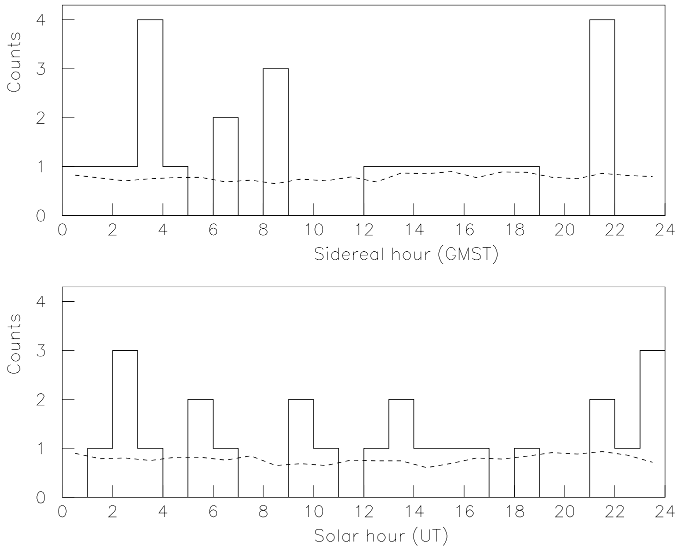

Figure 3. Number of coincidences n_c, indicated with the continuous line, and the average number $\bar{n}_a$ of accidentals, indicated with the dashed line (in total $n_c = 24$ and $\bar{n}_a = 18.8$), versus the sidereal (top) and solar hour (bottom).

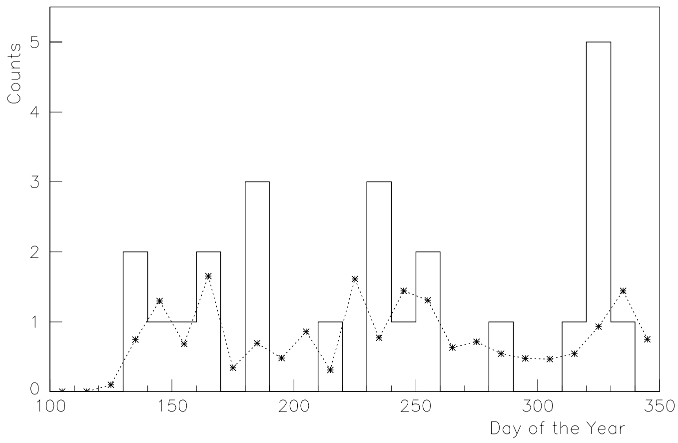

Figure 4. Number of coincidences n_c (solid line) and the average number $\bar{n}_a$ of accidentals (dashed line) as a function of the day of the year, in 10-day bins.

5. Upper limit evaluation

As a general remark, let us recall that the upper limit we are going to compute has simply the meaning of putting a limit on the total number of GW bursts that arrived at the Earth during our measurements. In no way can it be interpreted as an absolute and constant in time limit on the possible rate of GW: it is possible that there exist sources of GW signals that, similarly to many other kinds of phenomena, emit repeatedly during limited periods of time, and it is also possible that the rate of signals, even remaining Poissonian, changes in its average value over a time scale of days, months or years.

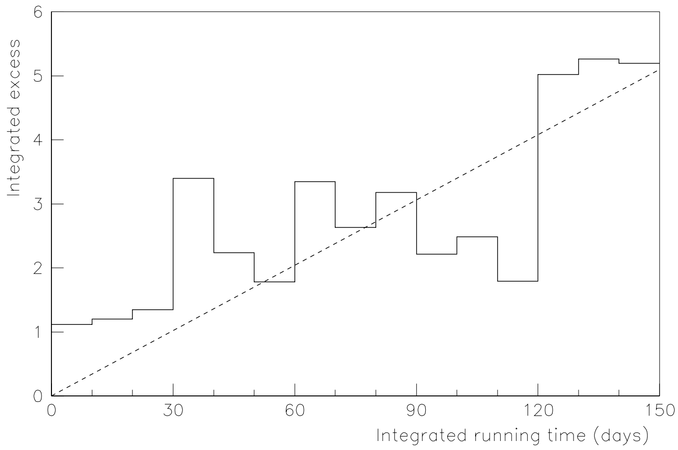

Figure 5. Excess of coincidences versus the integrated running time (solid line) and a linear fit (dashed line) giving a slope of ≃0.034 excess/day.

In order to compare with the most recent published upper limits (the one from the S2 LIGO run [6] and the one derived by the IGEC collaboration [4]) we adopted the same frequentist statistical approach and signal modelling.

We have computed with a Monte Carlo program the response of NAUTILUS and EXPLORER in coincidence for signals of different amplitudes, assuming as in the case of figure 14 of [6], optimal orientations of the detectors. A Gaussian noise, with a sigma equivalent to the median values reported in table 2, was added to each signal and then we applied the same threshold criteria as we used in the data analysis, i.e. we consider an event detected if its energy exceeds the SNR threshold of 19.5. In this way we derived the coincidence efficiency at each of the considered values of signal amplitude. At the same time we constructed the energy spectrum of the simulated coincidence events, more precisely the spectrum of the average between the EXPLORER and NAUTILUS energies. From this spectrum, we found, for each value of signal amplitude, the 10% lower point and we applied this threshold to the experimental coincidences, both in-time and delayed. The reason for putting such a threshold is to eliminate the cases of such very low energies as to be practically incompatible with the assumed signals. Such a low value of 10% has been chosen in order to be less sensitive to the calibration uncertainty. After the application of this threshold, obtaining n_c coincidences and n_a accidentals, we compute the value x such that the Poisson probability $P(\mu = n_a + x, n \leqslant n_c) = 0.05$. The rate upper limit at 95% confidence level is then approximately given by

$$\text{U.L.} = \frac{x}{0.9\epsilon_h T}, \tag{5}$$

where ϵ_h is the efficiency as a function of h as determined by the Monte Carlo, T is the total duration of the measurement (148.7 days in the present case) and the factor 0.9 takes into account the 10% energy threshold applied.

The results are shown in figure 6, where the LIGO and IGEC curves are taken from figure 14 of [6]. We used in the abscissa the root-sum-square amplitude h_{rss} for Gaussian signals with $\tau = 0.1$ ms computed as

$$h_{\text{rss}} = \frac{H(f)}{(2\pi)^{1/4}} \frac{\exp(\pi^2\tau^2 f^2)}{\sqrt{\tau}}, \tag{6}$$

where $H(f)$ is the Fourier transform of the GW signal at frequency f.

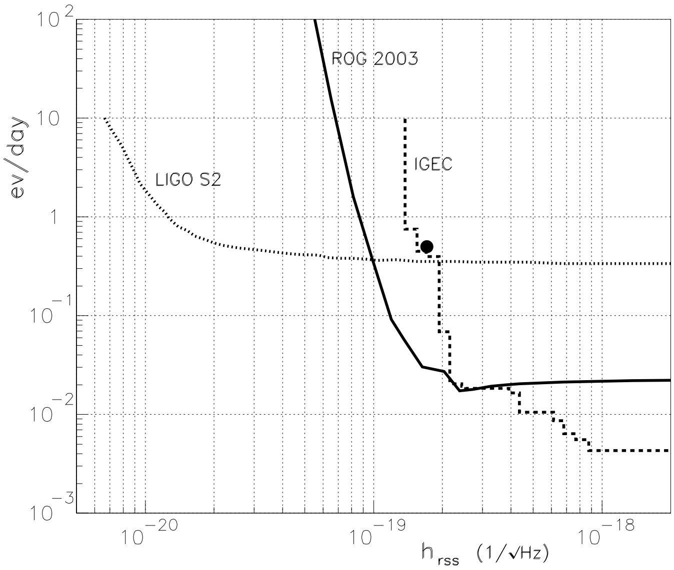

Figure 6. Upper limit (at 95%) on the rate of events arriving at Earth as a function of $h_{\rm rss}$, assuming Gaussian-shaped bursts with $\tau = 0.1$ ms. The LIGO and IGEC curves are from figure 14 of [6]. The large point represents roughly what could have been the rate deduced [21] from our 2001 results.

The value of $h_{\rm rss}$ is numerically related to the adimensional h (see equation (3) with $\Delta\nu = 1$ kHz) we use more commonly by $h_{\rm rss} \equiv 6.86 \times 10^{-2} h$.

Examining figure 6, we see that each curve is characterized by a very steep increase at lower values that is determined by, and actually represents, the sensitivity of the apparatus, and by a flat zone at higher values that is simply determined by the duration of the data taking. The comparison of our results with the previous ones thus shows that LIGO had already in the S2 run a much better sensitivity, while we improved, by about a factor of 2, the sensitivity with respect to the IGEC search.

6. Conclusions

During the year 2003, NAUTILUS and EXPLORER have operated with a common time of 148.7 days. The energy sensitivity was of the order of $T_{\rm eff} \sim 3$ mK corresponding to the detection with SNR = 1 of a conventional GW burst of amplitude $h \sim 4 \times 10^{-19}$, which is the best sensitivity reached so far for long data taking runs. Furthermore the improvement in the bandwidth of NAUTILUS, with respect to the previous 2001 run, allowed us to lower the coincidence window from about 0.5 s to ∼30 ms, lowering significantly the number of accidental coincidences.

The coincidence analysis gives 24 coincidence against 18.8 expected and the sidereal time analysis is not showing a significant departure from the background distribution, even if one can note that in the sidereal hours where there was an excess in the 2001 data, again now there are more coincidences than accidentals. We must remark that in 2003 we could not use the energy filter, while we did use it for the 2001 data.

The interpretation of the result of the 2001 run in terms of a possible continuous and uniform (in time) arrival of burst signals at h $\simeq 10^{-18}$ level is excluded by the present result at 95% confidence level.

EXPLORER and NAUTILUS are operating satisfactorily, actually slightly better than in 2003, and without long interruptions since early 2004, and we expect to complete this long run at the end of 2005.

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