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Seven years of data taking and analysis of data from the Explorer and Nautilus gravitational wave detectors

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Abstract
The two gravitational wave detectors Explorer (located at CERN) and Nautilus (in Frascati, LNF) have been operating for many years. These detectors allow us to investigate various classes of signals, such as bursts, continuous waves and the stochastic background. They operated in the years 2001 and 2003 with unprecedented sensitivities. In this paper we will recall some of the results obtained by the collaboration and summarize our plans for the near future.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

Resonant mass detectors [1] of gravitational waves (gw) are cylindrical bars, whose end face vibrates when the bar is hit by a gw. The bar end face displacement ΔL is proportional to the dimensionless wave amplitude $h \approx \frac{\Delta L}{L}$, where L is the length of the bar. The measurement of the displacement is done by means of transducers, well coupled to the bar, that convert the displacement into an electric signal. Typically, resonant mass detectors have two resonance frequencies, where the sensitivity is at its best. The parameters that determine the sensitivity are:

- the mass M of the bar. Given a material, the sensitivity improves with the mass;
- the temperature T of the bar. The sensitivity increases by cooling down the bar. In fact, the displacement of the bar end face due to the thermal noise depends on the square root of the temperature[1] ($\Delta L = 310^{-17}$ m at $T = 3$ K, $\Delta L = 10^{-17}$ m at $T = 300$ mK);
- the merit factor Q of the bar–transducer system, which determines the time the energy released by the signal remains into the bar. The higher the Q, the better the sensitivity.

[1] The cooling of the bar also brings other advantages, such as an increase in the merit factor and the possibility of using super-conducting, and hence low-noise, devices.

There are various resonant gw detectors in the world [2]. Explorer and Nautilus are the gw detectors of the ROG Collaboration.

The sensitivity to gw signals is determined by $\tilde{h}$, the noise spectral amplitude (or strain sensitivity), in units of $1/\sqrt{\text{Hz}}$. For example, for Nautilus 1999 at the resonances (and over a bandwidth of $\simeq$1 Hz) it was :

$$\tilde{h} \propto \sqrt{T/(MQ)} = 3 \cdot 10^{-22}/\sqrt{\text{Hz}}. \tag{1}$$

At that time Nautilus was cooled at 100 mK. The bandwidth of these detectors depends only on the transducer and amplifier. It can be increased by improving the coupling of the bar–transducer system and/or by reducing the noise temperature of the amplifier.

A larger observation bandwidth has already become a reality for Explorer and Nautilus, as described in [3]. The readout has been upgraded and, in particular, the transducer is a new small-gap capacitive transducer.

Recently, the Auriga detector has been cooled down again after major improvements on the system, and, as shown in [4], results are very promising.

Explorer and Nautilus strain sensitivities during the 2001 and 2003 runs are shown in figures 1 and 2. The upgrade for Explorer was done before the 2001 run and, for Nautilus, before the 2003 run. During the 2001 run the strain sensitivity of Explorer, cooled at 2.6 K, was less than $h \leqslant 3 \cdot 10^{-21}\ 1/\sqrt{\text{Hz}}$ over a bandwidth of $\simeq$10 Hz. During the 2003 run, due to a leakage problem, Explorer was cooled at 4 K and the sensitivity was a little bit affected. The Nautilus peak sensitivity is now of the order of $h \simeq 3 \cdot 10^{-21}\ 1/\sqrt{\text{Hz}}$, due to the fact that the detector is cooled at 2 K, but the bandwidth is highly increased, compared to the previous runs. As a result, the sensitivity to bursts for both the detectors has reached the best level ever obtained with this kind of detector, as will be discussed in the next section. We still expect improvement of these figures.

Resonant gw detectors have been operating for many years, with good sensitivities and very good duty cycles. Figure 3 shows the operation times, from 1 January 1997 to 13 June 2003. Data from the five detectors taken during the time period 1 Jan 1997–31 Dec 2000 have been exchanged within the IGEC (International Gravitational Event Collaboration) [5], to perform coincidence analysis in the search for 'short bursts'. A very good result has been the duty cycle of the observatory: over a time period of four years, at least one of the detectors was working over 1322 days, which means that the time coverage was 90%. Data have been jointly analysed and a new upper limit has been set [6].

2. Analysis for the detection of bursts

The problem is the detection of very small signals embedded in noise: the displacement produced by a signal emitted in a SN explosion that has released 1% M_0 into gw in the galaxy is $h \approx 10^{-18}$. This has to be compared with the displacement ΔL produced by the noise, which depends on the square root of the bar temperature. This is the core of the detection problem. To increase the *SNR*, defined as the ratio between the amplitude of a known shape signal h and the noise standard deviation σ_n it is necessary to filter the data [7, 8] using matched filters. But the noise of the detectors is, in general, non-stationary and the design of the filter must face this problem. Adaptive filters, where the spectral estimation is obtained using information on the actual noise, are a good tool for solving this problem [7, 9]. It is shown in [9] that the SNR improvement introduced by a filter can be expressed in terms of a reduction of the temperature from the temperature T to the effective temperature T_{eff}: $\text{SNR}_m/\text{SNR}_0 = T/T_{\text{eff}}$, where SNR_0 is the (energy) signal-to-noise ratio before the filtering and SNR_m is the (energy) signal-to-noise ratio after the filtering. For example, Explorer cooled at $T = 2.7$ K has an

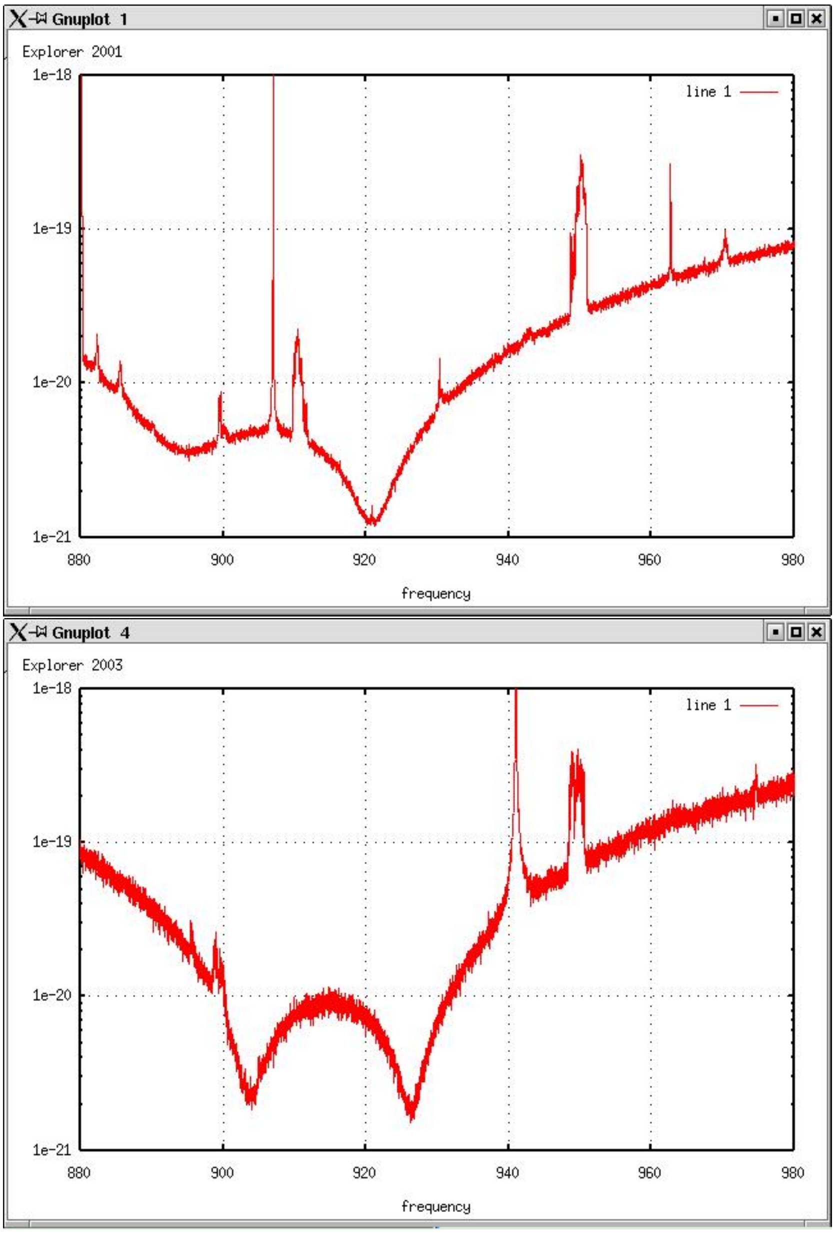

Figure 1. Explorer strain sensitivities during the 2001 run (top) and the 2003 run (bottom). The x-axis is the frequency, Hz, in the range 880–980 Hz. The y-axis is in units of $1/\sqrt{\text{Hz}}$ and ranges from 10^{-21} to 10^{-18}.

effective temperature of $T_{\text{eff}} = 1$–5 mK (this figure depends on the detector parameters and it increases with the bandwidth). T_{eff} [K] and h, the sensitivity to bursts, are related by

$$h \simeq \frac{L}{\tau_g v_s^2}\sqrt{\frac{kT_{\text{eff}}}{M}} \tag{2}$$

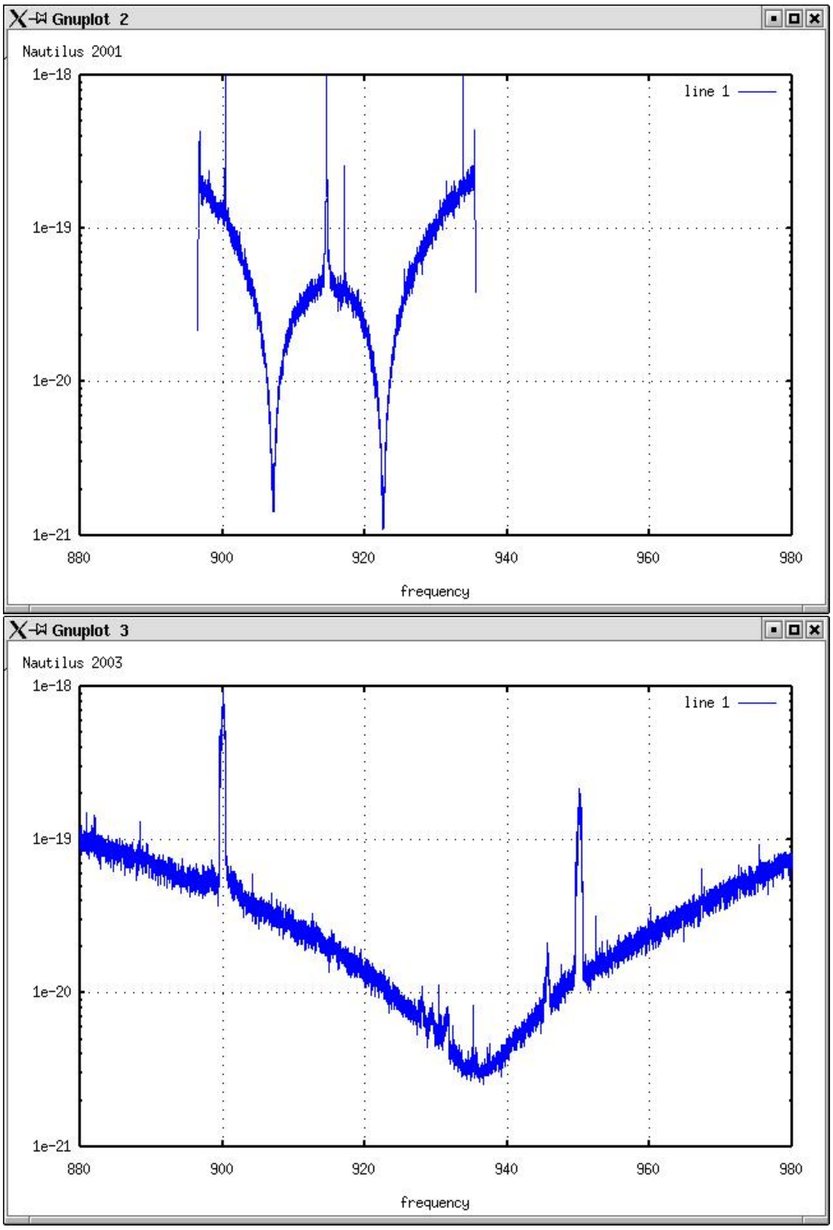

Figure 2. Nautilus strain sensitivities during the 2001 run (top) and the 2003 run (bottom). The *x*-axis is the frequency, Hz, in the range 880–980 Hz. The *y*-axis is in units of $1/\sqrt{\mathrm{Hz}}$ and ranges from 10^{-21} to 10^{-18}.

where L is the bar length ($L = 3$ m), M is the bar mass ($M = 2300$ kg), v_s is the sound velocity in the bar ($v_s = 5400$ m s^{-1} in Al) and τ_g is the pulse duration. Equation (2) holds if we suppose a constant noise spectrum over the detector bandwidth. Numerically, $h \simeq 7.97 \cdot 10^{-18}\sqrt{T_{\mathrm{eff}}}$, with T_{eff} in kelvin and $\tau_g = 1$ ms. Thus, $T_{\mathrm{eff}} = 1$ mK means a sensitivity to bursts $h \simeq 2.5 \cdot 10^{-19}$ (SNR = 1).

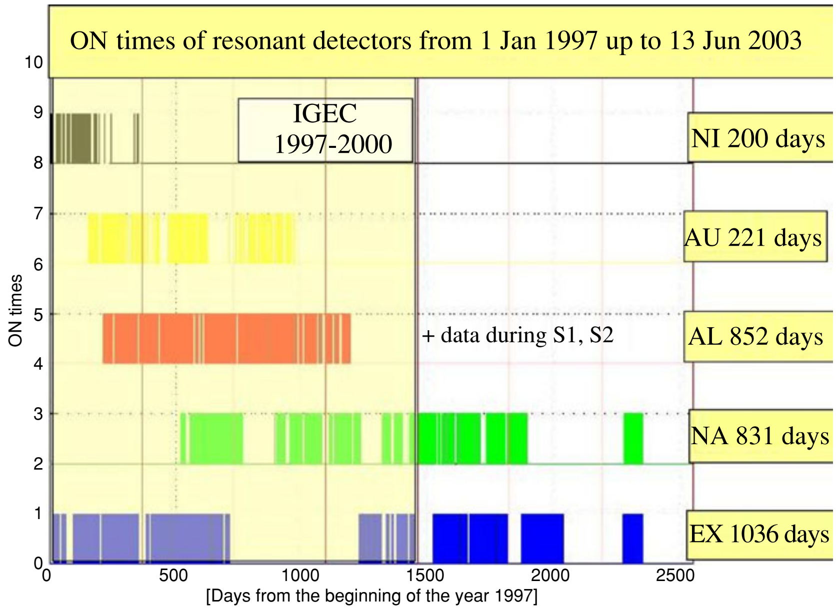

Figure 3. ON times, from 1 Jan 1997 up to 13 June 2003. The x-axis are days, from 1 Jan 1997. It ranges from 0 up to 2500. The y-axis is different for the various detectors (e.g., for Allegro it ranges from 4 (detector off) to 5 (detector on)). The total number of days of observation for each detector is indicated.

2.1. Coincidences among gw detectors

The classical approach to searching for bursts of gravitational radiation is based on the coincidence of detectors that have been operating simultaneously and have produced 'event' lists. This approach is reasonable in the case where the detectors are parallel, which is the present situation for the ROG detectors. In general, this is not possible (in particular, when performing coincidences in a network of resonant detectors and interferometers) and a different approach is needed. For example, in the case where the waveform of the signal is known, a 'coherent network search' can be used to increase the SNR of the combined network of interferometers/bars. This data analysis strategy effectively incorporates phase information using the antenna patterns and the time delays between the detectors, while combining the data from the detectors [10].

Various papers reporting results of coincidence analyses done using cryogenic resonant detectors have been published (see [11] and references therein). Relevant points of the coincidence analysis are listed here:

- when data are filtered, e.g. for delta-like signals, the output of the filter are events above given thresholds, but the events are only an estimation of the signals;
- the sensitivity of the detectors, and thus the threshold, varies with time;
- the sensitivities of the various detectors are, in general, different.

Thus the same signal generates, in the detectors, events that give a different estimation and have a different uncertainty on the energy and on the time of arrival of the signal itself. But, even in this situation, it is worth doing the coincidences. The analysis has to be done considering in an appropriate way the noise effect and the detection efficiency of each detector for given signals.

We have hence proposed and used algorithms based on the selection of the events on the basis of their compatibility with given signals [11].

3. The Explorer and Nautilus detectors in the 2001 run

In the year 2001, Explorer and Nautilus have worked with the best sensitivity to bursts reached at that time, and with a very good duty cycle.

We have analysed the data applying the energy selection criteria and performing a 'sidereal analysis', which means, roughly speaking, looking for interesting paths in the sidereal plane [12]. This is particularly 'easy' because the two detectors are parallel. We collected data at the level (for SNR $= 1$) $h \geqslant 6 \cdot 10^{-19}$.

The 'indication' which is provided by this data has been widely discussed [13–15]. As stated in [15], the lesson we learned is that the Explorer–Nautilus 2001 data, plotted as a function of a sensible physical quantity and compared with physically motivated models, does not provide the same information as any random sample. Indeed, the evidence in support of the models is not enough to modify strongly our beliefs, but it is certainly at the level of 'stay tuned, waiting for new data'.

4. The Explorer and Nautilus detectors in the 2003 run

We again put the detectors in operation at the beginning of 2003. We stress here that in order to do a proper sidereal analysis, many months of data are needed. In particular, the collection of data over a time period longer than one year is necessary to sensibly update beliefs on different models. In this run, we collected 258 days of data with the detector Explorer and 185 with Nautilus, at a sensitivity level better than $T_{\rm eff} = 8$ mK. Figure 4 shows the coincidence times for the operation of Explorer and Nautilus during the two runs of 2001 (126 days) and 2003 (160 days). Considering all the data collected (that is, without any selection on the data) the median values of the sensitivities are $T_{\rm eff} = 2.2, 2.5$ mK for Explorer, in 2001 and 2003, respectively, and $T_{\rm eff} = 2.8, 1.6$ mK for Nautilus. Figure 5 shows the histograms of the hourly averages expressed in terms of $T_{\rm eff}$, for both the detectors, during the two runs of 2001 and 2003. The sensitivities of the detectors in this new run are very good: if compared to those in the year 2001, Explorer is working roughly at the same level, while Nautilus is working with a sensitivity which is, on average, better by a factor $\simeq$2 due to the new configuration and, in particular, to the larger bandwidth.

The analysis of these data is presently in progress.

5. The search for continuous waves

A natural strategy for searching for monochromatic waves is to look for significant peaks in the spectrum. In this case the SNR increases with the observation time $t_{\rm obs}$: as $t_{\rm obs}$ increases, the frequency resolution of the spectrum increases—the frequency bin gets smaller $\delta\nu = 1/t_{\rm obs}$—thus the noise content in each bin decreases with $t_{\rm obs}$, while the signal is not dependent on the observation time. To estimate the power spectrum we use periodograms (squared modulus of the Fourier transform, FFT). For a periodic signal of amplitude h_c at the frequency $\bar{\nu}$ the periodogram gives ${h_c}^2$ with a noise contribution of $2S_h(\bar{\nu})\delta\nu$, $S_h(\bar{\nu})$ being the two-sided noise power spectrum of the detector (measured in Hz^{-1}). The SNR for periodic signals is

$$\mathrm{SNR} = \frac{{h_c}^2 t_{\rm obs}}{2S_h(\bar{\nu})}. \tag{3}$$

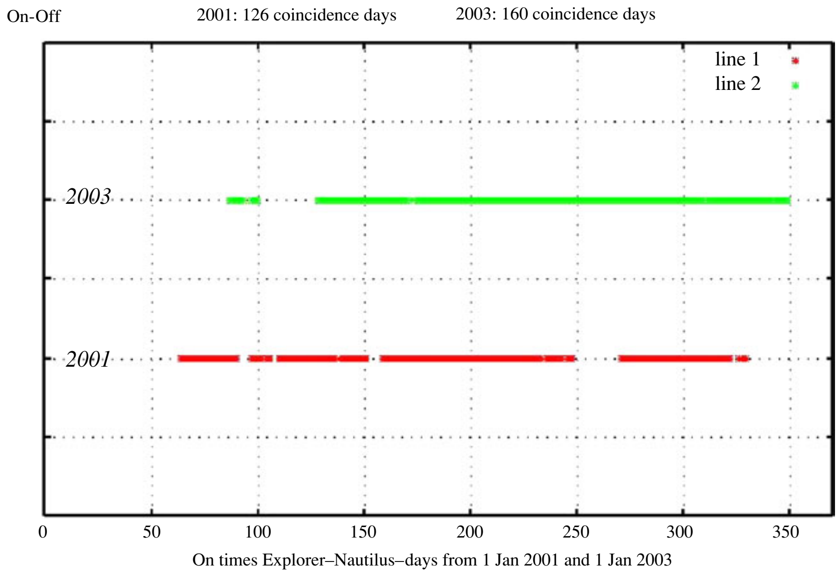

Figure 4. ON times of the coincidences between Explorer and Nautilus for the 2001 and 2003 runs. The *x*-axis are days of the year, from 0 up to 365. The *y*-axis refers to the two years (bottom line: 2001, top line: 2003). The coincidence days collected in the 2001 run are $\simeq$126, while in the 2003 run they are $\simeq$160.

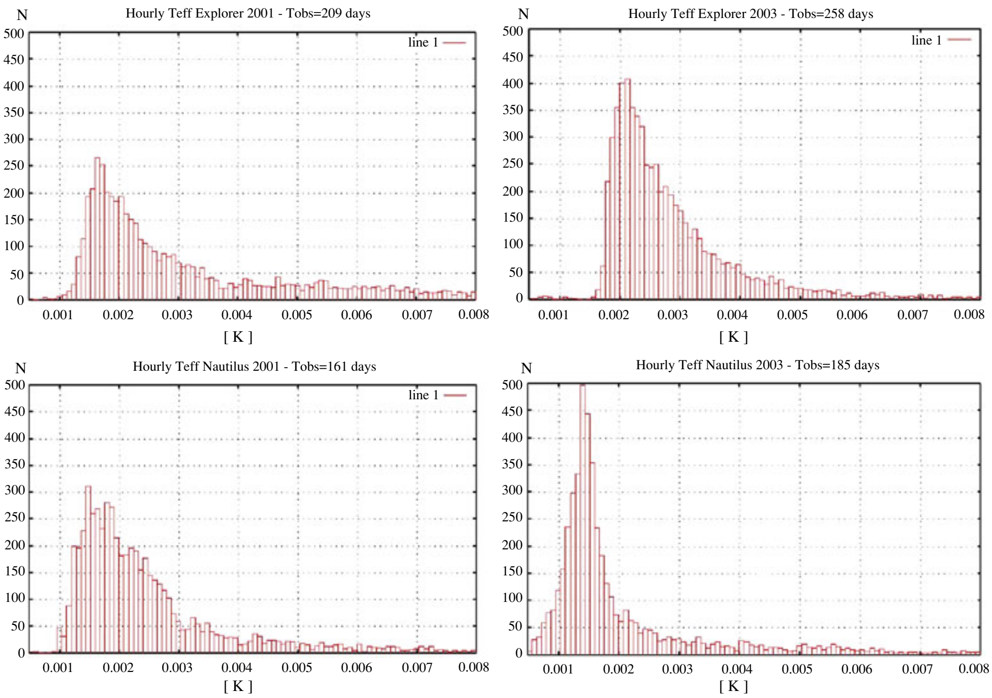

Figure 5. Histograms of the hourly averages, expressed in terms of T_{eff}, for both detectors, during the two runs 2001 and 2003. The *x*-axis is [K], (from 0.0005–0.008). The *y*-axis is the number, N, of hours in each bin. Top: Explorer; bottom: Nautilus.

Equation (3) holds if the instantaneous frequency of the continuous signal at the detector is known. The analysis procedure in this case is 'coherent', since the phase information is used. This is the case of 'targeted searches', where the source parameters are all known (frequency, location, spin-down).

In most cases it is impossible to perform a coherent analysis over all the data: the procedure is limited by the computational power, which increases with the high power of the observation time. This is the case of 'blind searches', where the source parameters are unknown and an 'all sky' search has to be performed. Hence, 'hierarchical procedures' are applied, which means that the observation time has to be divided into M sub-periods, such that the spectral resolution of the spectra becomes $\delta\nu' = M/t_{\mathrm{obs}}$ and the corresponding SNR is M times smaller than that in equation (3). These hierarchical strategies are based on iterations of two basic steps:

- incoherent, where the information from the data chunks is combined, but the phase information is lost;
- coherent, where matched filtering on M chunks of data is done.

The M spectra can be combined together by incoherent summation, that is, by averaging the square modulus (stacking procedure) or tracking lines in a time-frequency plane (tracking procedure, based on the Hough transform). We remark that there are various ways to implement these procedures. The Rome procedure is based on the construction of a frequency domain database, data quality inspection, incoherent Hough search with candidate selection (frequency, position, 2–3 spin-down parameters), coherent search on longer FFTs, only on the selected candidates and new incoherent and coherent steps, until the full length of data is reached. In the coherent step we partially correct the frequency shift due to the Doppler effect and spin-down, hence we can do longer FFTs and obtain higher resolution time-frequency maps. Recently, an interesting new idea was proposed by S Frasca, based on the fact that the signal is continuous: coincidences can be done between candidates selected with the incoherent search done over different time periods which will reduce the number of candidates to be analysed during the coherent step. This opens the possibility to increase by a large factor the length of the FFTs in the first coherent step.

A collaboration between ROG and Virgo–Rome has been established, to apply to Explorer and Nautilus data the Rome strategy for the pulsar search. We are developing software for the 'coherent steps', including general tools. This software is the PSS–Astro library, which is part of the library developed by the Virgo group in Rome. Documentation is available at the Web site http://grwavsf.roma1.infn.it/pss. We are also developing software for the creation of the frequency domain database for our data, using tools in the PSS and SNAG libraries, done by S Frasca. Our frequency domain database consists of 'elementary spectra', each obtained by performing the FFT of a given number of samples. Each elementary FFT has a header, containing information on the data, which can be used to set a threshold for vetoing the data.

An analysis has been performed on Explorer data, searching only for sources in the galactic centre [16]: no signals with amplitude greater than $h_c = 2.9 \cdot 10^{-24}$, in the frequency range (921.32–921.38) Hz, were observed using data collected over a time period of 95.7 days in 1991.

An overall sky search, based on the procedure in [17], has also been performed on Explorer 1991 data. The data have been extracted from the frequency domain database, following the procedure described in [16, 17]. The analysis is carried out on the basis of a memorandum of understanding between the ROG and the Institute of Mathematics of the Polish Academy of Sciences. We have analysed three sets of 2-day data over a bandwidth of 0.76 Hz around 922 Hz. We have shown that we are able to perform an all-sky 2-days-long coherent search of the narrow band data with no loss of signal of amplitude $h_c \geqslant 2.8 \cdot 10^{-23}$. The 2-day stretches of data are taken from a larger continuous set of data of almost 13 days. The UTC time of the first sample of the first set is 19 November 1991. The strain sensitivity of this data is very good: it is at the level of $\tilde{h} \leqslant 10^{-21}\ 1/\sqrt{\mathrm{Hz}}$ and also the level of stationarity of the data is very good. We have chosen an hexagonal grid over the sky and the number of filters is $N_{\mathrm{fft}} \approx 3.7 \cdot 10^8$ (see [17], sections VI and VII). The spin-down range is $-9.17 \cdot 10^{-8}$–$+9.17 \cdot 10^{-8}$ Hz s^{-1}. The search for candidates has now ended. We have three sets of candidates and we are now in the process of analysing the coincidences among them. Information and details about the analysis can be found at the Web site http://www.astro.uni.torun.pl/kb/AllSky/AllSky.html, written and maintained by Kazik Borkowski. The analysis will end this year. From the analysis of the candidates of the first stretch of data we have already set an upper limit, which is the first upper limit from an all-sky search for gravitational radiation from neutron stars [18]. This upper limit is at the level $h_c \leqslant 2 \times 10^{-23}$, and it applies in the small frequency range which has been exploited. From the joint analysis of the three sets of data we expect to improve this result. This analysis has been possible thanks to very good team work and collaboration among people (ROG, institutions in Poland and Virgo–Rome). Two other analyses, searching for continuous sources, are now being performed:

- we have an agreement with the AEI in Golm for the analysis of Nautilus 2001 data. The analysis will be done using the 'Merlin' cluster in Golm;
- we have an agreement with M Yvert (LAPP, Annecy), and F Vetrano and A Viceré (University of Urbino) to look for continuous signals from pulsars in binary systems, applying their Hough-based algorithms to Nautilus data.

6. Conclusions

Gw resonant detectors Explorer and Nautilus have been operating for many years and they reached very good sensitivities in the last 2001 and 2003 runs. Both Nautilus and Explorer are presently in operation. I have concentrated here only on topics related to the search for bursts and continuous waves, which do not cover all the activities we are running on the data. Given the fact that various gw detectors have already started data taking and others will start soon, collaboration among the groups is very important to establish the basis for future work within a network of different detectors.

References

[1] Astone P 2002 *Class. Quantum Grav.* **19** 1227
[2] Allegro: http://gravity.phys.lsu.edu
Auriga: http://www.auriga.lnl.infn.it
Explorer, Nautilus: http://www.roma1.infn.it/rog
Niobe: http://www.gravity.pd.uwa.edu.au
[3] Astone P *et al* 2003 *Phys. Rev. Lett.* **91** 11
[4] Auriga: http://www.auriga.lnl.infn.it/auriga/detector/run2_assembling/status.html
[5] IGEC site: http://igec.lnl.infn.it/
[6] Astone P *et al* 2003 *Phys. Rev.* D **68** 022001
[7] D'Antonio S 2002 *Class. Quantum Grav.* **19** 1499
[8] Ortolan A *et al* 2002 *Class. Quantum Grav.* **19** 1457
[9] Astone P, Buttiglione C, Frasca S, Pallottino G V and Pizzella G 1997 *Nuovo Cimento* C **20** 9–60
[10] Pai A, Dhurandhar S and Bose S 2001 *Phys. Rev.* D **64** 042004
[11] Astone P, D'Antonio S and Pizzella G 2002 *Class. Quantum Grav.* **19** 1443
[12] Astone P *et al* 2002 *Class. Quantum Grav.* **19** 5449

[13] Finn S L 2002 *Class. Quantum Grav.* **20** L37
[14] Astone P *et al* 2002 *Class. Quantum Grav.* **20** S785
[15] Astone P, D' Agostini G and D' Antonio S 2002 *Class. Quantum Grav.* **20** S769
[16] Astone P *et al* 2002 *Phys. Rev.* D **65** 022001
[17] Astone P, Borkowski P, Jaranowski P and Krolak A 2002 *Phys. Rev.* D **65** 042003
[18] Astone P *et al* 2003 *Class. Quantum Grav.* **20** S665