IL NUOVO CIMENTO Vol. 27 C, N. 5 Settembre-Ottobre 2004
DOI 10.1393/ncc/i2005-10006-8

NAUTILUS and EXPLORER: Present status and recent data analysis

L. Quintieri
INFN, Laboratori Nazionali di Frascati - Frascati (Rome), Italy

(ricevuto il 20 Gennaio 2005)

Summary. — This paper describes the present status of the two detectors NAUTILUS and EXPLORER, the most sensitive resonant gravitational-wave antennas nowadays working in the world, and reports the results from the recent data analysis.

PACS `04.80.Nn` – Gravitational wave detectors and experiments.
PACS `95.55.Ym` – Gravitational radiation detectors; mass spectrometers; and other instrumentation and techniques.
PACS `95.30.Sf` – Relativity and gravitation.
PACS `95.85.Sz` – Gravitational radiation, magnetic fields, and other observations.

1. – Theoretical prediction

Comparing Newton's theory of gravity with Einstein's General Relativity, the most radical change that we can find in the behaviour of the gravity is that Einstein's gravity predicts *waves*. General relativity, in fact, asserts that the geometrical curvature induced by a mass does not arise everywhere instantaneously, but it travels outward from its source at speed of light. Thus, if a massive object changes its shape or if it undergoes an acceleration, the space curvature around it will be modified and this perturbation will propagate away as *gravitational waves*. Therefore, a gravitational wave can be defined as a time-varying distorsion of the geometry of space, that temporarily changes the distance between any given pair of points. In such a way any object, once invested by a gravitational wave, is stretched and shrunk together with the space-time in which it is placed. For this reason the amplitude of a gravitational wave is described by a fractional change in length (*strain deformation* h).

Since the emission of gravitational radiation is a relativistic effect, huge masses undergoing very strong accelerations are required in order to have detectable gravitational waves. No man-made apparatus can produce gravitational waves with enough energy to be measured with any available instrument at present time. The only possible sources are energetic astrophysical systems, capable to release huge amount of energy in gravitational waves.

2. – Gravitational signals from different sources

Astrophysical sources [1] of gravitational waves can be essentially grouped into three classes according to the emission mechanism of gravitational radiation.

- *Burst sources.* Gravitational-wave bursts are high-energy emissions lasting a very short time (few milliseconds). This kind of sources includes: non-spherically symmetric explosion of supernovae, merging of compact binary systems, etc. The expected strain perturbation due to a supernova explosion, that can be observed from the Earth is given by the following formula:

$$h = 1.7 \times 10^{-20} \frac{10\ \text{Mpc}}{R} \sqrt{\frac{M_{\text{gw}}}{M_{\odot}}} \tag{1}$$

  where R is the distance between the source and the Earth, M_{gw} is the mass converted in gravitational radiation and $M_{\odot}$ is the solar mass. Unfortunately the expected rate of these events is a few over a century in our Galaxy. If also the Virgo Cluster is included in the observation volume, the rate increases to 1 event per week but the strength of these waves, being inversely proportional to the distance from the source, should be some order of magnitude weaker. For eample, the non-spherically symmetric collapse of a star of $M = 6M_{\odot}$ at the centre of our Galaxy would produce waves with an amplitude on the Earth of about $h \simeq 3 \times 10^{-17}$ [2]. The same event in the Virgo Cluster would generate a wave that will reach the Earth with an amplitude of $h \simeq 3 \times 10^{-20}$.

- *Continuous sources.* Continuous waves are due to periodic mass shift, from which the gravitational waves will be sustained. Typical sources of continuous waves are rotating compact objects, binary systems, pulsars, etc. It is worth to mention that the observation of the PSR 1913+16 binary system allowed Hulse and Taylor to give an indirect evidence of the existence of the gravitational waves. For this work, in fact, they obtained the Nobel Prize in 1993. The measurements over 17 years of the decreasing rotational period of this system shows that the system is loosing energy in full accordance (within an error less than 0.1 %) with the General Relativity prediction.

- *Stochastic background.* This background is made of gravitational waves emitted at Planck time, that is 10^{-43}s after the big-bang. The spectrum of the primordial stochastic background covers a very wide frequency range: from 10^{-18} Hz to 10^{4} Hz. The direct measurement of these gravitational waves would give a fundamental help for understanding the origin of the universe.

3. – The detection of gravitational waves

Since Einstein's General Relativity formulation, the direct detection of gravitational waves is one of the most extraordinary challenges of experimental physics. Unfortunately the sources are expected to be rare or extremely weak (or both). Consequently the instruments devoted to detect gravitational waves must be very sensitive and should be working with the highest possible duty cycle. This means that we need to employ the best available technologies to guarantee a search in the largest volume of space possible

Table I. – *Main characteristics of the cryogenic resonant detectors Nautilus and Explorer.*

	Explorer	Nautilus
Mass (kg)	2270	2220
Material	Al5056	Al5056
Length (m)	2.97	2.94
Diameter (m)	0.6	0.6
Temperature (K)	2.5	0.130
Resonance (Hz)	915	935

and for the longest observation time. General Relativity has already gathered spectacular successes in various tests, but it still needs the detection of gravitational waves in order to have a full experimental confirmation. In spite of this aspect, the real importance of detecting gravitational waves consists in founding a new astronomy able to extend our knowledge of the universe. Indeed the measurement of gravitational waves will help answering very important astrophysical questions otherwise not explicable by any other means. For example, gravitational-wave astronomy should be able to determine the abundance of neutron stars, which material these are really made of, or detect binary systems containing black holes, that is something that conventional astronomy could not discern. Furthermore gravitational-wave observation could be complementary to conventional astronomy, offering the means to better understand, for example, the motions of the matter that drive supernova explosions. Moreover, in a very ambitious task, the cosmologists also hope that gravitational waves might help to reveal how masses were displaced after the Big Bang.

The experiments for the search of gravitational waves started in the early sixties at the University of Maryland thanks to Joseph Weber [3]. Since then the detection technique has been strongly improved exploiting the progress in mechanics (attenuation system), cryogenics (working at very low temperature) and electronics (low-noise amplifier). Even if the conceptual scheme of the resonant detectors has not been modified since Weber time, the energy sensitivity of this kind of detectors, espressed in terms of h, has been improved by a factor more than 10^4.

Explorer, already operating in 1983, was the first cryogenic resonant detector able to achieve, since 1990, long-term observation. In the following years other resonant detectors started to operate and a new generation of interferometers has been conceived and developed.

Explorer and Nautilus are the two cryogenic resonant detectors managed by the ROG collaboration. They are the gravitational detectors that up to now recorded the largest amount of data and reached the best sensitivity.

4. – Resonant detectors: working principles and experimental configurations

Weber-style detector consists of a massive cylinder of aluminum, which is hung horizontally by a single cable around its middle section. A sensitive transducer is placed at one end to measure vibrations of the cylinder at its first longitudinal frequency f_{b}, which could be induced by the impinging gravitational wave.

In particular, Explorer and Nautilus are equipped with a resonant capacitive transducer that consists of a fixed flat plate bolted to one end of the antenna and of a vibrating disk, that represents the resonating mass, m_{t}. In such a way we realize a system of two

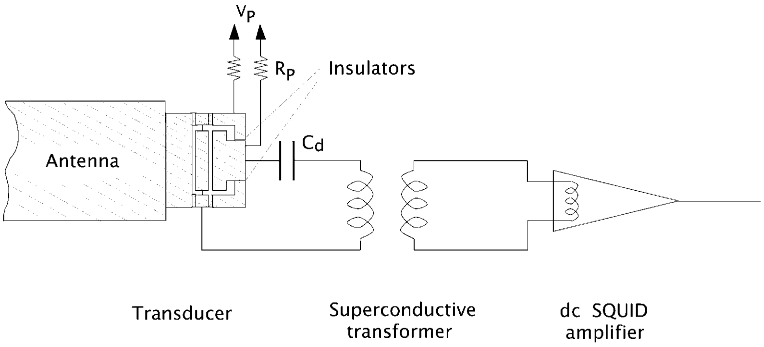

Fig. 1. – Read-out circuit.

coupled oscillators, so that the antenna vibration energy can be effectively transferred as mechanical energy to the resonant mass of the transducer.

In order to have an efficient amplification of the mechanical response of the bar, the transducer must have a light resonating mass ($m_\mathrm{t} = 0.7$ kg in the case of Nautilus and Explorer) and must be coupled and tuned near the bar resonance, so that $f_\mathrm{t} \simeq f_\mathrm{b}$, where f_t indicates the mechanical resonance frequency of the transducer. To convert the mechanical energy in an electric signal, the two faces of the capacitor are held at a fixed voltage, whose intensity affects the coupling between the oscillators. The resulting frequencies f_+ and f_-(1) of the two normal modes collect most of the signal energy absorbed by the antenna and most of the thermal noise of both oscillators.

To reduce the thermal noise and consequently increase the signal-to-noise ratio (SNR), the resonant mass is cooled to liquid-helium temperature or below. Explorer is cooled at the superfluid helium ($T \simeq 2.2$ K), while Nautilus can reach a temperature near 0.1 K being equipped with a dilution refrigerator.

The electric field applied to the transducer allows to transform the displacement of the resonant masses into an electric signal that is then amplified by a low-noise d.c. SQUID(2) amplifier.

A superconductive transformer matches the high transducer capacitance to the low impedance of the SQUID.

The second resonant matching stage is the LC circuit formed by the transducer capacitance and the transformer inductance.

The main characteristics of Nautilus and Explorer are given in table I, while the experimental set-up is shown in fig. 1.

---

(1) In well-coupled oscillators $f_\mathrm{t} = f_\mathrm{b}$ and the two resulting normal modes have frequency: $f_\pm \simeq f_\mathrm{b}(1 \pm \sqrt{\mu})$ where μ is the ratio of the equivalent mass of the two oscillators, that is $M/2$ for the bar and m_t for the transducer.

(2) A d.c SQUID (Superconducting QUantum Device) is a superconductive magnetometer that works like flux-to-voltage transducer. It is made of superconductive loops interrupted by two Josephsons links [4].

5. – Sensitivity of resonant detectors for gravitational waves

At the beginning of the experimental search for gravitational waves, the main scientific goal was detecting bursts due to gravitational collapse and, therefore, the resonant antennas have been originally conceived, designed and optimized for impulsive signals. For this reason, the resonant detector sensitivity is usually expressed in terms of the minimum amplitude h detectable by the apparatus or, in equivalent way, by the minimum detectable energy change, ΔE_{min}, induced by an *impulsive signal* in the antenna.

We use to indicate with T_{eff} (effective temperature of the detector) the noise temperature, in Kelvin units, for burst detection, that is the average value of the noise after applying to the data a filter matched to delta-like signal. Therfore, the T_{eff} can be directly related to the minimum detectable energy innovation by the following equation:

$$\Delta E_{\mathrm{min}} = k_{\mathrm{B}} T_{\mathrm{eff}} \tag{2}$$

where k_{B} is the Boltzmann constant.

All the main efforts to obtain the best sensitivity are, obviously, addressed to lowering the T_{eff} value, in order to be more effective in the detection of gravitational-waves signals with small energy SNR.

In the transfer function of the bar with a perfectly tuned transducer, supposing the interaction of the electrical resonator LC with the mechanical ones can be neglected, we can easily obtain the dependence of T_{eff}, at each resonance mode, on the principal system parameters [5]:

$$T_{\mathrm{eff}} \propto \frac{\phi_{\mathrm{n}}}{\alpha}\sqrt{\frac{f_{\pm}}{Q}}\sqrt{m_{\mathrm{t}} \cdot T}\,, \tag{3}$$

where

- $f_{\pm}$ = mode resonance frequency,
- Q = quality factor of the mode,
- T= thermodynamic temperature of the bar,
- ϕ_{n} = SQUID wide band flux noise expressed in units of $\phi_0/\sqrt{\mathrm{Hz}}$(3),
- m_{t} = resonant transducer mass,
- $\alpha \propto C_{\mathrm{t}} E N M_{\mathrm{s}}$ = coefficient that relates the magnetic flux in the SQUID to the mechanical displacement of the resonant transducer [5] . C_{t} is the transducer capacitance, N the impedance matching transformer ratio, E the electrical field in the transducer and M_{s} the mutual inductance between the SQUID and its input inductance.

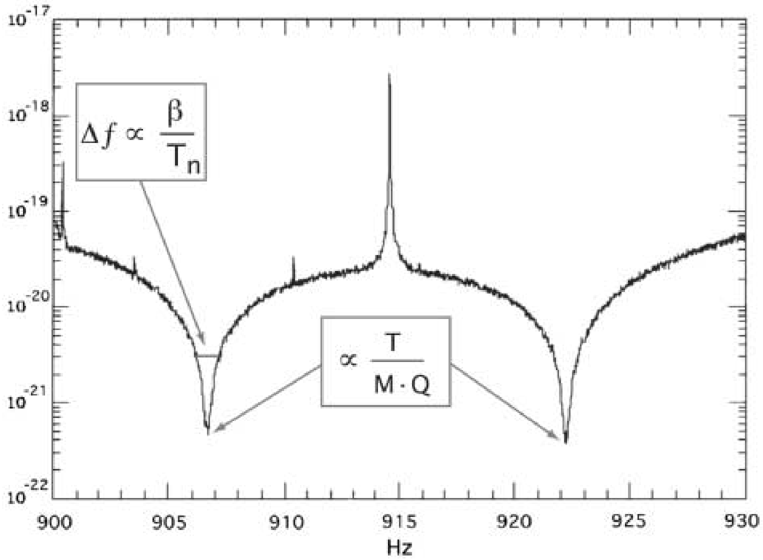

Fig. 2. – Resonant detector spectral density $\tilde{h}$.

Another way to express the bar sensitivity is by defining the strain noise spectral density $S_h(\nu)$ or, in equivalent way, its square root $\tilde{h} = \sqrt{S_h(\nu)}$ (the spectral amplitude). The power spectrum $S_h(\nu)$ is the Fourier transform of the system response when the input signal is equal to the total noise, so that $S_h(\nu)$ gives the power spectrum of the gravitational potential h that can be detected for SNR = 1. In the case of resonant detectors the spectral density has minima at the resonance frequencies (see fig. 2) where the sensitivity for gravitational waves turns to be

$$S_h(f_\pm) = (\tilde{h})^2 = \frac{\pi}{2} \frac{kT_\mathrm{e}}{MQv^2} \frac{1}{f_\pm} \,, \tag{4}$$

where

- T_e = thermodynamic temperature of the detector plus a term due to the transducer back-action. This is negligible when a SQUID amplifier is used.

- M = mass of the detector.

- v = sound velocity in the detector material.

Another important figure that defines the performance of a resonant detector is the frequency bandwidth Δf, that is the frequency region where the antenna is sensitive.

---

(3) $\phi_0 = 2.07 \times 10^{-15}$ Wb is the flux quantum.

It is possible to show that frequency bandwidth depends on the transducer-amplifier chain:

$$\Delta f = \frac{f_\pm}{Q\sqrt{\Gamma}}, \qquad \text{where } \Gamma = \frac{T_\mathrm{n}}{2\beta QT} \tag{5}$$

and

- $T_\mathrm{n} \propto \phi_\mathrm{n}$= electronic voltage noise of the amplifier expressed in Kelvin units,
- $\beta \propto \left(\frac{\alpha}{M_\mathrm{s}}\right)^2$= the fraction of mechanical energy that the transducer is capable of converting in electrical energy.

Γ is the ratio between the spectral power densities of the wide-band electronic noise and the narrow-band Brownian noise of the bar. In a detector equipped with a very-low-noise amplifier (nearly quantum limited), Δf could approach 100 Hz.

The physical parameters of the antenna $M, L, f_\pm$ and the thermodynamic temperature T are fixed in a given detector, so the most significant improvements of a bar detector sensitivity can be achieved by decreasing the contribution of the electronic noise T_n and increasing the coupling β of the transducer to the SQUID.

The main efforts of the groups involved in resonant detectors, during the last several years, have been devoted in this direction and the significant results obtained by the ROG collaboration will be discussed in what follows.

6. – Latest upgrades on Explorer and Nautilus

During Nautilus and Explorer's operating life, data-taking phases have been alternated with periods devoted to upgrade the experiments in order to achieve even better sensitivity. The latest upgrades on Explorer and Nautilus were done in 1999 and 2002, respectively. Since then, Explorer and Nautilus have been working with unprecedented sensitivity collecting for the longest periods data streams of good quality.

6˙1. *The Explorer case.* – A very important change in the read-out system concerned the capacitive transducer: the old "mushroom"-shaped transducer with a gap of 50 μm was replaced with the new "rosette-shape" one, having a gap of 10 μm (fig. 3). This innovative design was conceived and developed by the ROG group [6] and has been used since the beginning of 2000 in Explorer and since 2003 in Nautilus. The geometry of the "rosette"-shaped transducer allows a gap much smaller than that reachable with the old one. The consequent capacitance $C_\mathrm{t} = 11$ nF is more than three times larger than that of the past transducers. The transducer mechanical Q is about 2×10^6 and the overall Q expected for the system is around 5×10^6 in the absence of electrical losses.

The d.c.-SQUID used is a commercial single-stage device produced by Quantum Design, with an input flux noise Φ_n comparable to that measured with the previously used SQUID. However, the efficiency in transferring the vibrational energy of the bar into electromagnetic energy in the final amplifier has been improved by using an input SQUID coil of mutual inductance $M_\mathrm{s} = 10\,\mathrm{nH}$, providing a coupling three times larger than in the past.

Finally, the changes performed in the read-out system have increased the coupling between the mechanical and electrical parts of the circuit, decreasing Γ by a factor larger than 100.

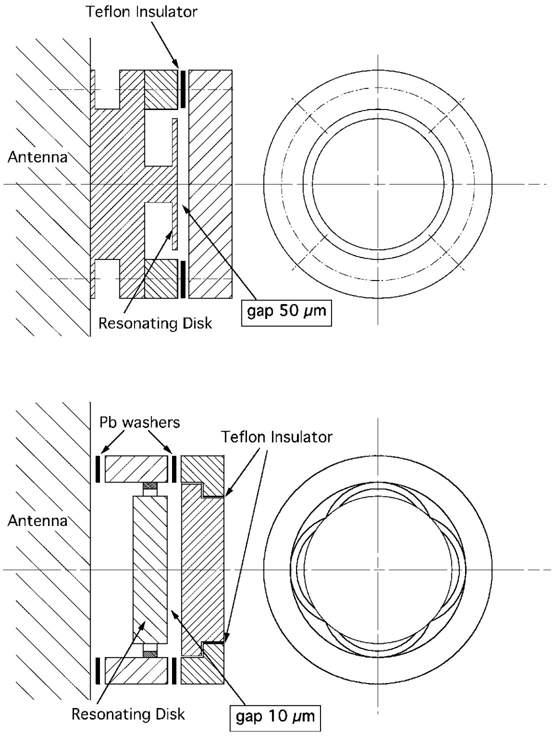

Fig. 3. – The old "mushroom"-shaped transducer and the new "rosette"-shaped one.

Explorer is now working with a burst sensitivity of $h \simeq 4 \times 10^{-19}$ and a noise temperature less than 3 mK over an operation duty cycle exceeding 80%, the main interruptions being due to cryogenic refills once every two weeks (see fig. 4).

As shown in fig. 5, the strain noise in the case of Explorer is at present $\tilde{h} \simeq 3 \times 10^{-21}\text{Hz}^{-1/2}$ over a bandwidth of 6 Hz and $\tilde{h} \simeq 10^{-20}\text{Hz}^{-1/2}$ over a bandwidth larger than 50 Hz. Before the 1999 upgrade the bandwidth corresponding to the strain sensitivity $\tilde{h} \simeq 10^{-20}\text{Hz}^{-1/2}$ was about a fifth of the present one, *i.e.* 6–10 Hz.

6˙2. *The Nautilus case.* – The improvements made on the Nautilus apparatus, during the stop in 2002, concerned not only the read-out chain, but some mechanical upgrades were also carried out. The bar was replaced by a new one with the first longitudinal frequency at 935 Hz, in order to tune the detector on twice the frequency where the remnant pulsar of SN1987A was observed [7].

A new suspension cable, that constitutes the final stage of the mechanical attenuation system, has been mounted. The new cable has been designed in order to eliminate some flexural resonances of the cable from the region of best attenuation, around the longitudinal resonance of the bar. The diameter of the new cable has been increased from 9 to 11 mm, giving in such a way a more stable position setting to the bar.

After the last upgrade, Nautilus is in data taking since May 2003, cooled at 3.5 K. The resulting strain noise is $\tilde{h} \simeq 2 \times 10^{-21}\text{Hz}^{-1/2}$ around 935 Hz and $\tilde{h} \leq 10^{-20}\text{Hz}^{-1/2}$ over about 30 Hz, as is shown in fig. 6.

The noise temperature is of the order of 1 mK, corresponding to a minimum detectable

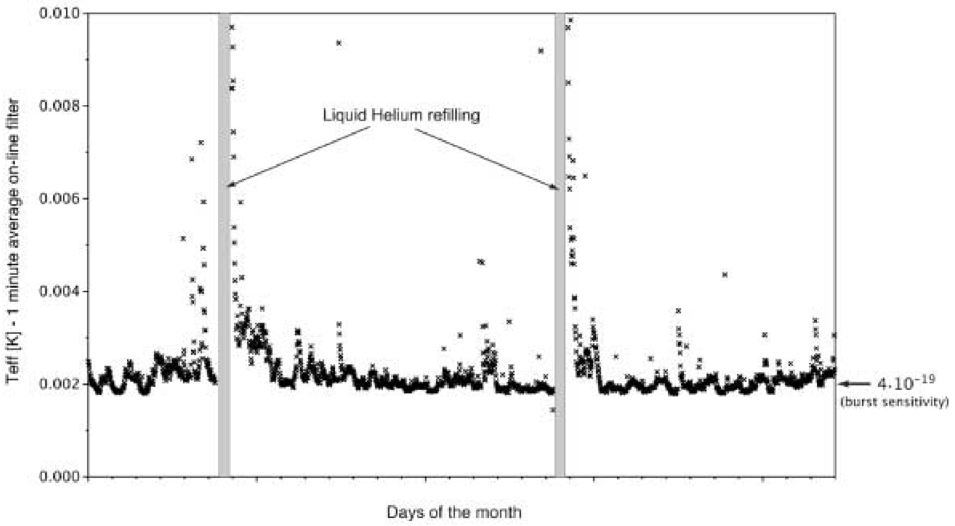

Fig. 4. – Effective temperature of the Explorer detector after 1998 upgrade.

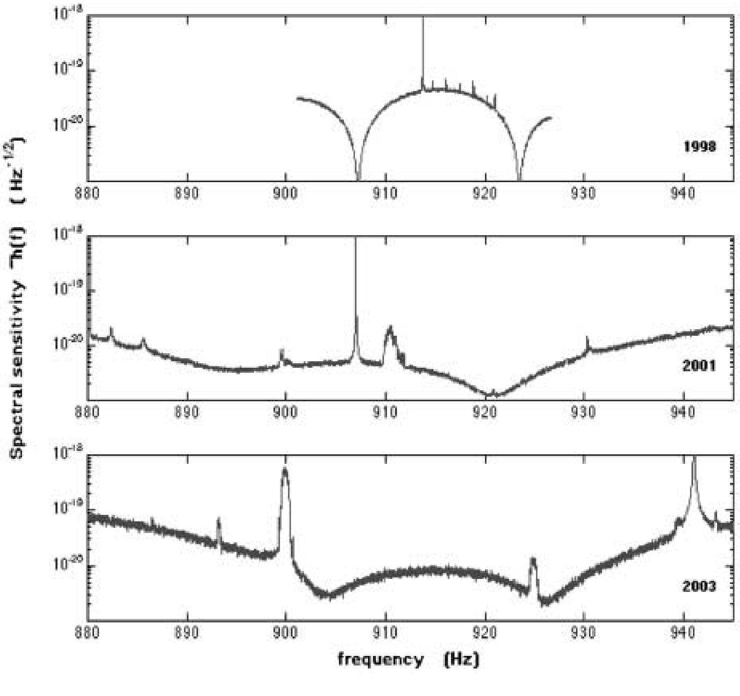

Fig. 5. – The spectral sensitivity of the Explorer detector. Top: in 1998, before the hardware upgrade. Middle: 2001 spectrum. Bottom: recent spectrum with the transducer resonator well tuned to the antenna. In all spectra, the lines rising above the mean level are due to either calibration signal or to disturbances of the power line.

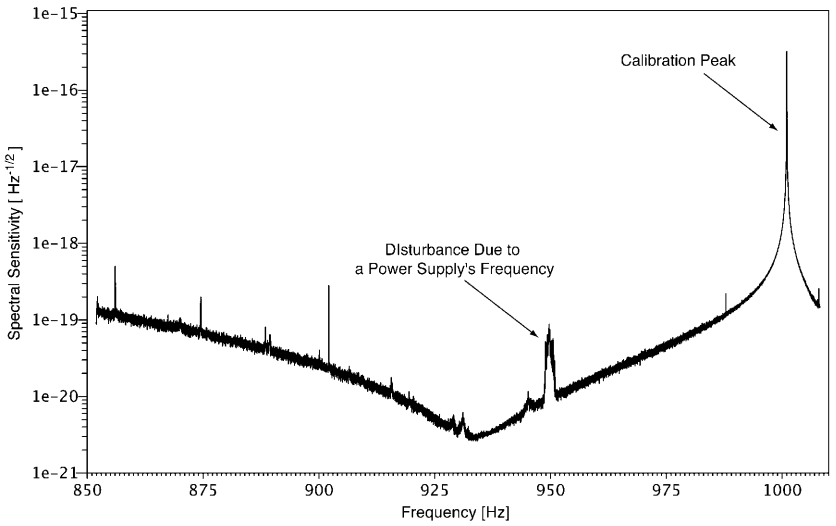

Fig. 6. – Nautilus spectral density at 3.5 K after 2002 upgrades.

wave amplitude $h_0 = 2.5 \times 10^{-19}$, for 90% of the time (fig. 7).

Better performance are expected when the system will be cooled down to 0.1 K, putting into operation the dilution refrigerator.

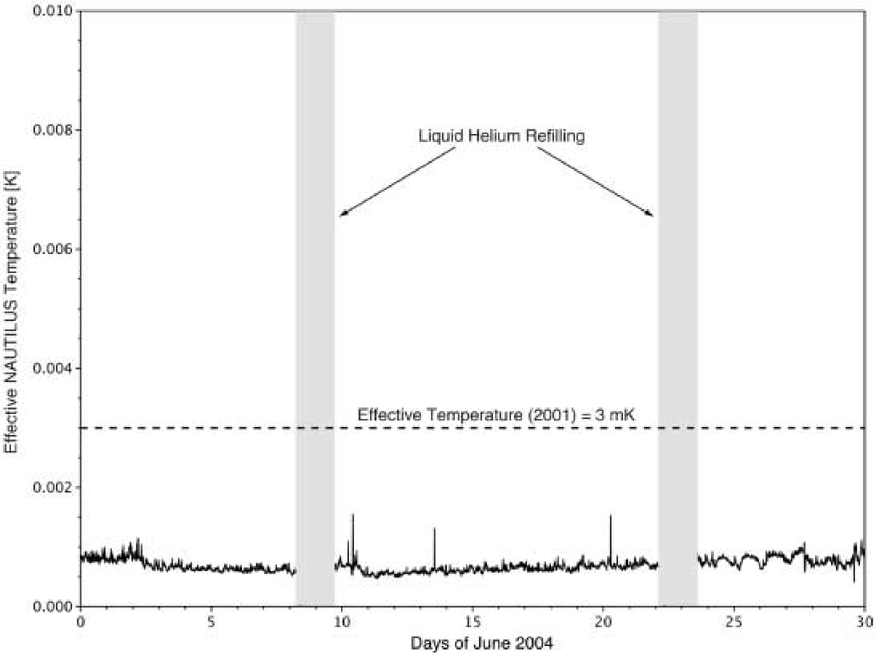

Fig. 7. – Effective Nautilus temperature before and after 2002 upgrade.

7. – Experimental results

The recent results of data analysis for different possible sources of signals will be summarized in the following, with the exception of the 2001 results for burst coincidence analysis. These will be discussed in more details in the next section.

- *Monochromatic signals.* A search for monochromatic signals coming from the Galactic Centre has been performed using 95.7 days of Explorer's data [8]. The upper limit of $h = 3 \times 10^{-24}$ has been given, in the range 921.32–921.38 Hz. An overall sky search in the band frequency from 921.00 Hz to 921.76 Hz for gravitational continuous sources located everywhere in the sky has also been developed using 13 days of data taken by the Explorer detector during November 1991 [9]. The main result of this analysis is an upper limit of 2×10^{-23} for the dimensionless amplitude h. A search for signals from the galactic disc or from some globular cluster has been planned in the frame of a collaboration between the ROG group and the Albert Einstein Max Planck Institute, using the Nautilus 2001 data.
- *Stochastic background.* A first cross-correlation analysis between Explorer and Nautilus to estimate the gravitational-wave stochastic background was published in 1999 [10]. Using 17 h of the Explorer and Nautilus data, an upper limit on the gravitational-wave energy density Ω_{gw} has been obtained: $\Omega_{\mathrm{gw}}(f) \leq 60$. The measure of the stochastic background depends on the square root of the bandwidth, so that, with the present configurations of Nautilus and Explorer, the cross-correlation analysis can take advantage of the larger overlapping between the respective bandwidths and so improve the previous upper limit for Ω_{gw}.
- *Correlations with gamma-ray bursts detectors.* Searches for correlations between the output of the gravitational-wave detectors Explorer and Nautilus and a list of of gamma-ray bursts detected by BATSE and Beppo-SAX satellites have been performed. GW detector data collected between 1991 and 1999 have been correlated to the GRB flux peak times, searching for an association between the gravitational-wave detector energy and GRBs at zero delay. The cumulative analysis of a large number of GRBs allows to obtain an upper bound on the gravitational-wave amplitude associated with GRB of $h \simeq 2.5 \cdot 10^{-19}$ [11].
- *Cosmic rays.* For the first time in 1999 the passage of cosmic rays has been observed to excite mechanical vibrations in the resonant detector Nautilus [12]. Almost all Nautilus events have been found to be in agreement with the thermoacustic model [13-16] with the exception of some extraordinary large signals that have been detected during the 1998 run at a rate much higher than expected [17]. This anomalous response of the resonant-mass gravitational-wave detector Nautilus could be due to the superconducting state of the bar, since Nautilus was working below the superconducting transition temperature when the large signals were detected. The experiment RAP (Rivelazione Acustica di Particelle) is in progress at the INFN Frascati National Laboratories in order to test this temperature dependence [18].

8. – 2001 coincidence analysis for burst signals

The search for short bursts of gravitational radiation is based on the coincidences found between the lists of candidate events obtained independently of the involved detectors. We briefly recall the definition of *event* in our analysis. Let be $x(t)$ the filtered

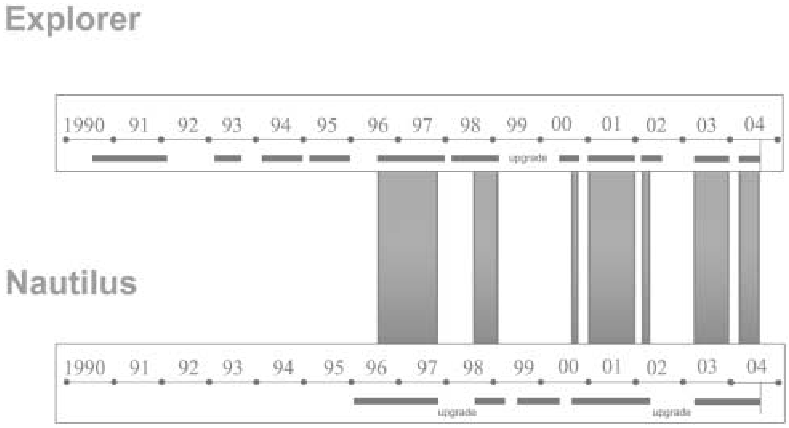

Fig. 8. – Simultaneous data taking in the last 14 years.

output of our detector, normalized in such a way that $x^2(t)$ gives the energy E of the oscillation expressed in Kelvin units. For extracting an event we set a threshold that corresponds to an energy $E_\mathrm{T} = 19.5\ T_\mathrm{eff}$. This threshold is set in order to obtain about one hundred of events per day. When $|x|$ grows above the threshold, its time behaviour is considered until it returns below the threshold for more than 3 seconds. The maximum amplitude and its occurrence time define an *event*.

In fig. 8 the simultaneous data-taking phases have been put in evidence during last 14 years. In particular in 2001 the two detectors have taken simultaneously data for 1488 hours.

During 2001 Nautilus and Explorer were the only two operating resonant detectors, with good sensitivity. The low-noise temperature on both detectors makes the 2001 data particularly interesting.

The analysis of coincidences for the 2001 data [19] was developed using two new important tools, which have proved to be useful and powerful in the search of signals with small SNR:

1. *Energy consistence.* A selection criterion for the coincidence events was introduced in the burst analysis based on the energy compatibility of the events, already applied for the 1998 data. The energy filter is applied with the aim of reducing the background, that is the number of accidentals(^{4}), taking into account the physical characteristic of the detectors. *In fact, all coincidences, whose corresponding event energies are so different in the two detectors that they cannot be ascribed to a common cause are rejected.* This rule can be stated in rigourous statistical terms [19];

(^{4}) Coincidences between the two detectors found at zero delay could be casual. We define *accidentals* the coincidences that occur by chance. They are estimated using algorithms based on the time shift procedure [20]. In fact, shifting the time of occurrence of the events of one of the two detectors a certain number of times we can construct the distribution of the so-called "*delayed*" coincidences. This distribution gives the statistical properties of the background, with respect to which, in the case of coincidence excess, we can estimate the probability that the excess is accidental.

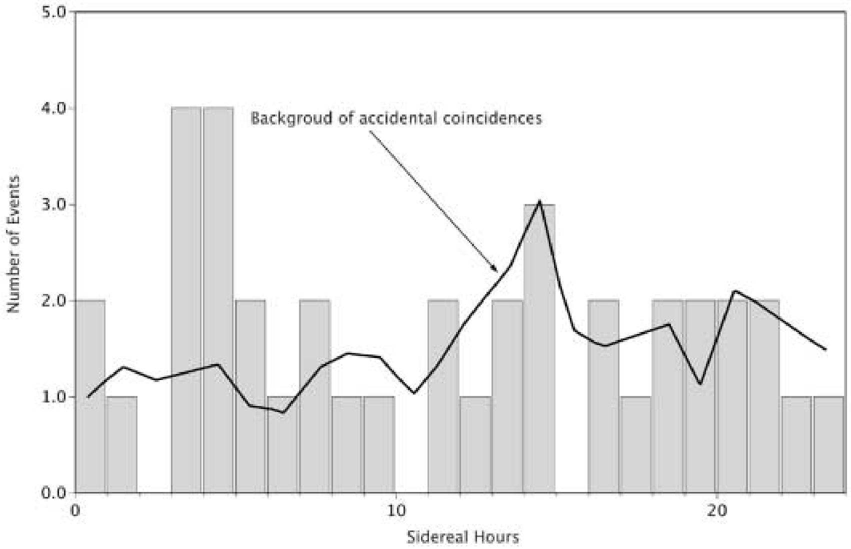

Fig. 9. – Explorer and Nautilus 2001 coincidence data analysis.

2. *Coincidences vs. sidereal time.* A sidereal-time analysis has been performed in order to be able to recognize a modulation in the intensity of the supposed gravitational signals, assuming, in accordance with the experimental observations, that we are looking for sources in the Galaxy, outside the solar system.

Figure 9 shows a histogram of excess of coincidences *vs.* the sidereal time, the continuous line being the number of accidentals.

We notice that having broadened the bandwidth of the detectors has turned out very convenient not only to collect more useful signals but mainly, with respect to the coincidence analysis, to shorten the coincidence time window and therefore to reduce the number of accidental coincidences with smaller time uncertainty of the events.

The analysis of coincidences between data recorded by Nautilus and Explorer during this year shows an excess of coincidences around the sidereal hour 4 (8 total coincidences over a background of accidentals about equal 1.9). The excess of coincidences occurs when the two bars are *favourably* oriented with respect to the galactic disk. In fact, the sensitivity of the cylindrical detectors depends on the direction of the impinging wave. For a gravitational-wave energy flux $\mathcal{F}(\nu)$, the energy absorbed by the first longitudinal mode of the bar can be calculated by means of the cross section Σ from the following equation:

$$E_{\text{abs}} = \Sigma \cdot \mathcal{F}(\nu)\,, \tag{6}$$

while the macroscopic gravitational cross-section Σ can be explicitly expressed in terms of the geometrical and physical parameters of the antenna by the following one [21, 22]:

$$\Sigma = \frac{8}{\pi}\left(\frac{G}{c}\right)\left(\frac{v}{c}\right)^2 M \sin^4\theta \cos^2 2\psi\,, \tag{7}$$

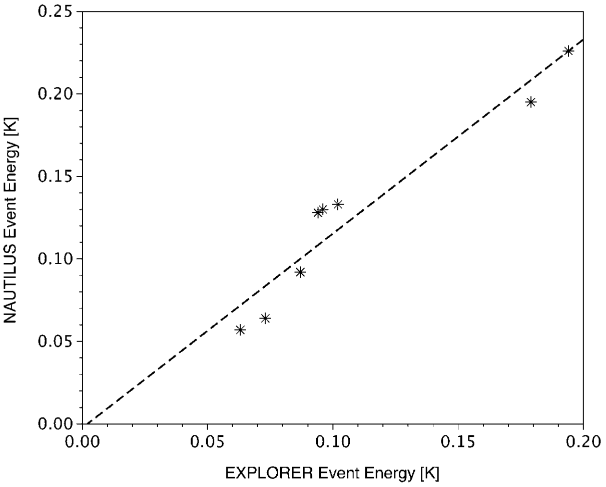

Fig. 10. – Explorer and Nautilus coincidence's energy correlation for the eight coincidences that occurred in the sidereal hour interval 3 to 5. The correlation coefficient is 0.96. Obviously, no energy filter was applied to perform this test.

where v is the sound velocity (equal to 5400 m/s in the Al5056 alloy at room temperature), c is the speed of light, G the gravitational constant, θ is the angle between the cylinder axis and the direction of propagation of the wave, ψ is the angle between the polarization plane and that formed by the bar axis and the direction to the source.

As the Earth rotates around its axis, during the day, the detector occurs to be variably oriented with respect to a given source at unknown location.

Because of the $\sin^4 \theta$ dependence of the cross-section, the bar reaches the best sensitivity when the impinging waves have the propagation vectors perpendicular to the cylinder axis. Between the sidereal hours 3 and 5, Nautilus and Explorer axes are perpendicular to the galactic disk and consequently they can see with the best sensitivity all signals coming from the Galaxy.

This is a relevant aspect in favour of the physical reliability of the excess found, even if, due the low statistic, new data must be collected in order to further argue about the nature of what Nautilus and Explorer have simultaneously observed.

It is worth to remark that the largest excesses of coincidences occur in two neighbouring hours, and this reinforces the statistical significance of these coincidences, the events in each hour being totally independent of those in a different hour. It has been shown [23] that the accidentals have a Poissonian distribution and the probability to have by chance a number of coincidences $\geq n_{\mathrm{c}}$ (observed ones) has been estimated. In particular, the probability that the coincidence peaks between sidereal hours 3 and 5 have occurred by chance is about 1%.

It is also important to stress that the coincidences found in sidereal hours 3-5 are strongly correlated in energy (see fig. 10) with a correlation coefficient equal to 0.96. This means that the measured energies of the coincident events are *compatible* with the same excitation.

An interesting task is to verify whether the coincidence excess found in the sidereal hour 4 is compatible with possible sources. If the source were located in the Galactic Center we would have found a coincidence excess twice a day. Since we see only one peak a day we can reasonably suppose that the sources are located on the whole Galactic Disk. The coincidence excess found between sidereal hour 3 and 5 is roughly $n_\mathrm{c} - n_\mathrm{a} \simeq 6$ over an effective time of observation equals to $1488 \cdot \frac{2}{24} \simeq 124$ hours, that is about 5 days, corresponding to an estimated rate of about one coincidence per day. The coincidences have an energy of about 100 mK that corresponds to a a burst amplitude of $h \simeq 10^{-18}$ and to an isotropic conversion into gravitational wave of $4 \cdot 10^{-3}$ solar masses, with sources located at a distance of 8 kpc. According to the amplitudes and the rate of these candidate events, the estimated value of the mass M_gw, converted per year in gravitational waves, is compatible with the known structure and the estimated mean life of our Galaxy.

REFERENCES

[1] Schutz B. F., *Class. Quantum Grav.*, **16** (1999) A131.
[2] Pizzella G, *Fisica Sperimentale del Campo Gravitazionale* (Edizioni NIS, La Nuova Italia Scientifica) 1993.
[3] Weber J., *Phys. Rev. Lett.*, **22** (1969) 1320.
[4] Tinkham M., *Introduction to Superconductivity* (Dover) 2004.
[5] Bassan M. and Pizzella G., *SIS-Pubblicazioni-LNF*, **95/064 P** (11-December-1995).
[6] Bassan M., Minenkov Y. and Simonetti R., *Advances in linear transducers for resonant gravitational wave antennas*, in *Proceedings of Virgo Conference on Gravitational waves: Sources and Detectors*; edited by Ciufolini I. and Fidecaro F. (World Scientific, Singapore) 1997, pp. 225-228.
[7] Middleditch J. *et al.*, *New Astron.*, **5** (2000) 243.
[8] Astone P. *et al.*, *Phys. Rev. D*, **65** (2001) 022001.
[9] Astone P. *et al.*, *Class. Quantum Grav.*, **20** (2003) S665.
[10] Astone P. *et al.*, *Astron. Astrophys.*, **351** (1999) 811.
[11] Astone P. *et al.*, *Phys. Rev. D*, **71** (2005) 042001.
[12] Astone P. *et al.*, *Phys. Rev. Lett.*, **84** (2000) 14.
[13] Grassi Strini A. M., Strini G. and Tagliaferri G., *J. Appl. Phys.*, **51** (1980) 849.
[14] van Albada G. D. *et al.*, *Rev. Sci. Instrum.*, **71** (2000) 1345.
[15] Bernard C., De Rujula A. and Lautrup B., *Nucl. Phys. B*, **242** (1984) 93;
[16] Amaldi E. and Pizzella G., *Nuovo Cimento*, **9** (1986) 612.
[17] Astone P. *et al.*, *Phys. Lett. B*, **499** (2001) 16.
[18] Bertolucci S. *et al.*, *Class. Quantum Grav.*, **21** (2004) S1197.
[19] Astone P. *et al.*, *Class. Quantum Grav.*, **18** (2001) 243.
[20] Astone P., Frasca S. and Pizzella G., *Int. J. Mod. Phys. D*, **9** (200) 341.
[21] Pizzella G., *SIS-Pubblicazioni-LNF*, **95/057 P** (10-November-1995).
[22] Paik H. J. and Wagoner V., *Phys. Rev. Lett. D*, **13** (1976) 10.
[23] Astone P. *et al.*, *Class. Quantum Grav.*, **19** (2002) 5449.