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The next science run of the gravitational wave detector NAUTILUS

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Abstract

The ultra-cryogenic gravitational wave detector NAUTILUS is gathering data in Frascati (Rome), in its second science run since June 1998. The measured strain sensitivity at the two resonances is 4×10^{-22} Hz$^{-1/2}$ over a bandwidth of 1 Hz and better than 3×10^{-20} Hz$^{-1/2}$ over a band of about 25 Hz, with a duty cycle of about 80%, mainly limited by cryogenic operations. At the beginning of 2002, the detector will be upgraded with a new Al bar, transducer and SQUID, and will be tuned to the 935 Hz frequency of the recently discovered pulsar in SN 1987A. The future sensitivity of the detector is presented and discussed.

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1. Introduction

NAUTILUS, the ultra-cryogenic resonant gravitational wave (GW) detector operated by the ROG Collaboration at the INFN Frascati National Laboratories [1], started its second science run in June 1998, after a partial overhaul of its mechanical suspensions and thermal contacts. We summarize here the results obtained so far and the goal of the next science run, which is scheduled for May 2002.

Let us recall the NAUTILUS main features. A layout of the NAUTILUS is shown in figure 1. The Al 5056 cylindrical bar has a mass of 2350 kg, length of 3 m and diameter

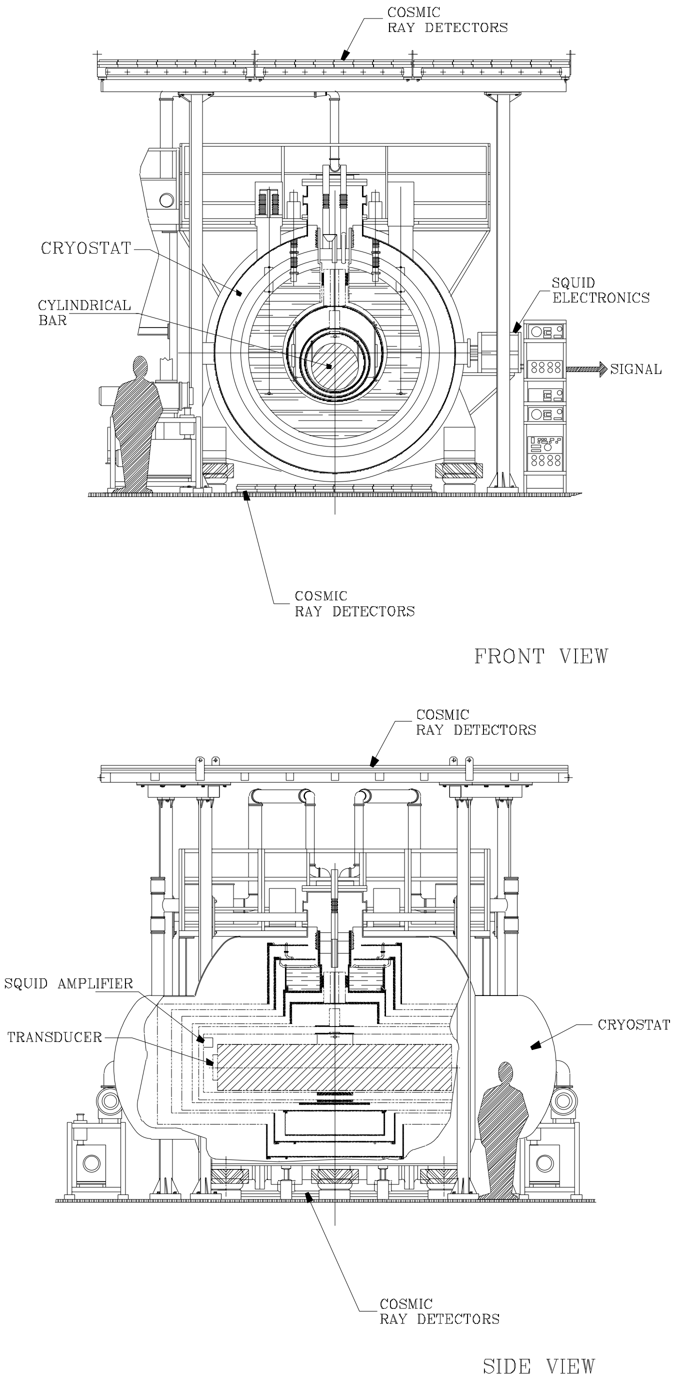

Figure 1. The NAUTILUS GW detector.

of 0.6 m. It is suspended by a U-shaped OFHC copper cable, wrapped around the bar central section and hung from the central ring of the innermost thermal shield of the cryostat. The bar is cooled to a temperature of about 0.1 K by a special ^{3}He–^{4}He dilution refrigerator contained in the cryostat top central access. The refrigerator mixing chamber (its coldest part) is in thermal contact with the ends of an OFHC copper suspension cable, which provides a suitable thermal path to the bar.

The vibrations of the bar are converted into electrical signals by a resonant capacitive transducer. The transducer and the bar form a system of two coupled oscillators. The frequencies ($f_- = 907$ Hz and $f_+ = 923$ Hz) of the resulting normal modes have a spacing of about $f_b\mu^{1/2}$, where $\mu = 3.031 \times 10^{-4}$ is the ratio between the effective masses of the transducer resonator and the bar.

The signals are applied to the input coil of a dc SQUID amplifier by means of a superconducting transformer, which provides the required impedance matching. The dc SQUID is biased with a dc current and an ac modulation flux at $f_m \approx 90$ kHz, applied through a coil, and is operated in the flux-locked loop configuration. Its output signal is applied to a low-noise differential FET amplifier through a cooled LC resonant circuit (tank circuit) tuned at f_m, which provides the proper noise impedance matching. The FET amplifier is followed by a lock-in amplifier, driven at f_m, whose output $V(t)$ is fed back to the SQUID via a weakly coupled coil in order to stabilize its operating point and linearize its input–output (V/ϕ) characteristics.

The output signal from the SQUID instrumentation is sent to the 5 kHz data acquisition system, which is connected to the international network and can be remotely operated. This machine performs the acquisition and permanent recording of the data in a form suitable for further off-line analysis and various functions of online analysis for diagnostic and monitoring purposes.

The experimental apparatus includes vibration sensors (accelerometers) and a magnetic-field sensor (search coil) both located on the cryostat. These sensors monitor the environment of the laboratory. Their output signals may be used as a veto. Another signal, which is used as a veto, is the output of the antenna seen through the SQUID instrumentation and bandpass filtered between 20 and 70 Hz.

The detector has also been equipped with a cosmic ray veto system consisting of layers of streamer tubes [2] placed above and below the antenna cryostat. A cosmic ray detector is needed because extensive air showers or energetic single particles (muons or hadrons) interacting in the antenna may produce signals simulating a GW burst.

2. Results of the second science run

The results obtained since June 1998 show a considerable improvement in the rejection of non-stationary noise and in the sensitivity of the apparatus, with respect to the first science run 1995–7 [1, 3].

We show in figure 2 the strain sensitivity of the detector, expressed in units of Hz$^{-1/2}$: it is the square root of the function usually denoted by $S_h(f)$, representing the input GW spectrum that would produce a signal equal to the noise spectrum actually observed at the output of the antenna instrumentation. The peak sensitivity is obtained at the frequencies of the modes and mainly depends on the factor T/Q, which is the ratio of the bar temperature to the mode quality factor. The detector bandwidth (of the order of 1 Hz) is determined by the ratio of the transducer coupling factor to the amplifier noise temperature. We show in figure 3 the detector noise temperature over a sample period of 3 days. This sensitivity allows the detection, at SNR $= 1$, of an impulsive GW signal of duration 1 ms at amplitude $h \simeq 4 \times 10^{-19}$.

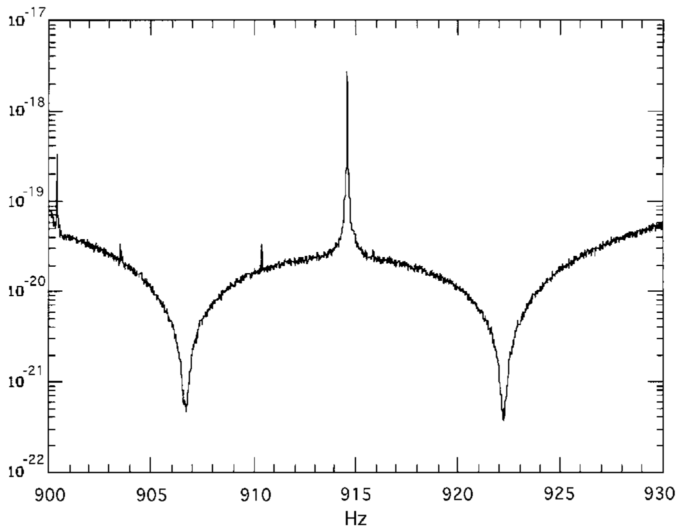

Figure 2. Experimental strain sensitivity of the NAUTILUS (input noise spectral amplitude in units of $\mathrm{Hz}^{-1/2}$). The sensitivity at the two resonances is about $4 \times 10^{-22}\ \mathrm{Hz}^{-1/2}$. The spectral amplitude is better than $3 \times 10^{-20}\ \mathrm{Hz}^{-1/2}$ over a band of about 25 Hz. The central peak at 914.6 Hz is a calibration reference signal fed into the dc SQUID amplifier to monitor the gain of the electronics.

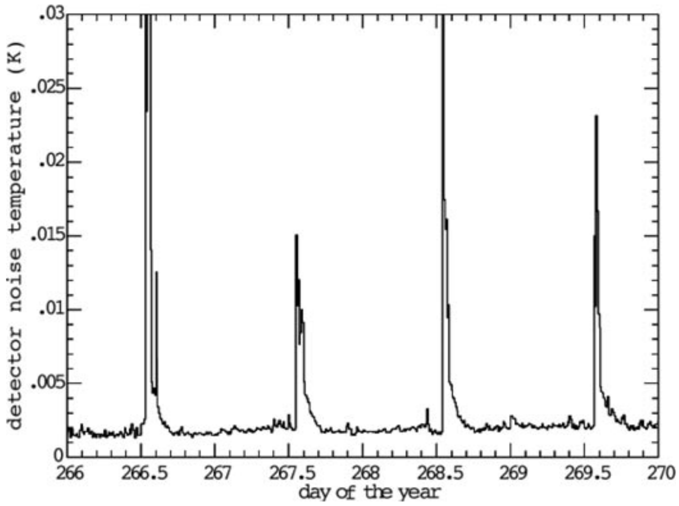

Figure 3. Detector noise temperature versus time, averaged over 10 min, for a period of 3 days. A noise temperature of 2 mK corresponds to a minimum detectable amplitude h of a GW burst of duration 1 ms, $h = 4 \times 10^{-19}$. The peaks are due to a daily cryogenic operation.

The main results of the second science run are summarized as follows:

- New upper limit to short GW bursts, from the search for coincidences among all the five IGEC (International Gravitational Event Collaboration) resonant detectors [4]. In particular, no event in coincidence above $h = 4 \times 10^{-18}$ has been detected in the 90-day period when three detectors were simultaneously operating. Analysis of the 1997–8 data released under the IGEC protocol has been completed and is reported in these proceedings.

- The first cross-correlation between the data of two cryogenic detectors for the measurement of the GW stochastic background [5] has been carried out. The results obtained with the detectors EXPLORER and NAUTILUS, tuned in February 1997 at 907 Hz, give a new direct upper limit on the GW energy density in the Universe, $\Omega_{\mathrm{GW}} < 60$.
- For the first time, the passage of cosmic rays (extensive air showers) has been observed to excite acoustic vibrations in a resonant mass, with the NAUTILUS in coincidence with our cosmic ray detector [6]. In the ongoing analysis of the data, we found new results, i.e. unexpected energetic events, when the Al bar is in the superconducting state [7], reported at this conference.
- A search for monochromatic signal is in progress and appropriate algorithms have been developed [8]. The present sensitivity of the NAUTILUS would allow us to get SNR = 1 for a continuous GW signal at the frequency of one of the two modes of amplitude $h \simeq 3 \times 10^{-25}$ with an observation time of 1 month.

3. The third science run

For the third science run, scheduled to start in spring 2002, we will upgrade the NAUTILUS with a new read-out system, similar to the one which is showing very good performances on our EXPLORER detector at CERN (see contribution in these proceedings). The read-out consists of the new rosette transducer [9] developed in our group, a new high-Q superconducting transformer and a quantum design dc SQUID.

The main goal of this third run is to get an unprecedented sensitivity for continuous signals at the frequency of about 935 Hz.

Middleditch *et al* [10] reported evidence of a faint optical pulsar, remnant of the SN 1987A in the large magellanic cloud. The measurements indicate that the pulsar has a period of 2.14 ms, modulation period of about 1000 s and spindown rate of 2–3 $\times$ 10^{-10} Hz s^{-1}. The spindown of a normal pulsar is believed to be caused by magnetic dipole radiation and relativistic pulsar winds. However, the low luminosity reported in the electromagnetic spectrum of this pulsar and the fact that the relation between spindown rate and modulation period can be explained at the same time by the existence of a non-axisymmetric component of the moment of inertia, support the idea that the spindown can be caused by radiating gravitational waves.

In this case, we can estimate the amplitude of the GW as [11]

$$h \sim 4.7 \times 10^{-26} \left(\frac{I}{1.1 \times 10^{45}\ \mathrm{g\,cm^2}} \right) \left(\frac{\epsilon}{10^{-6}} \right) \left(\frac{f_g}{935\ \mathrm{Hz}} \right)^2 \left(\frac{50\ \mathrm{kpc}}{D} \right) \tag{1}$$

where I is the moment of inertia of the neutron star, ϵ its non-axisymmetric oblateness, D its distance from the Earth and f_g the frequency of the GW signal (two times the pulsar rotational frequency).

We now evaluate the sensitivity of the NAUTILUS required to observe such a signal.

The problem of extracting a signal of a given shape $h(t)$ from a noise with given spectrum $S_h(f)$ is exhaustively treated in information theory. The optimum performance of a detector is obtained by filtering the output with a filter matched to the signal. The energy signal-to-noise ratio (SNR) of the filtered output is given by the well known formula

$$\mathrm{SNR} = \int_{-\infty}^{+\infty} \frac{|H(f)|^2}{S_h(f)}\,\mathrm{d}f \tag{2}$$

where $H(f)$ is the Fourier transform of $h(t)$.

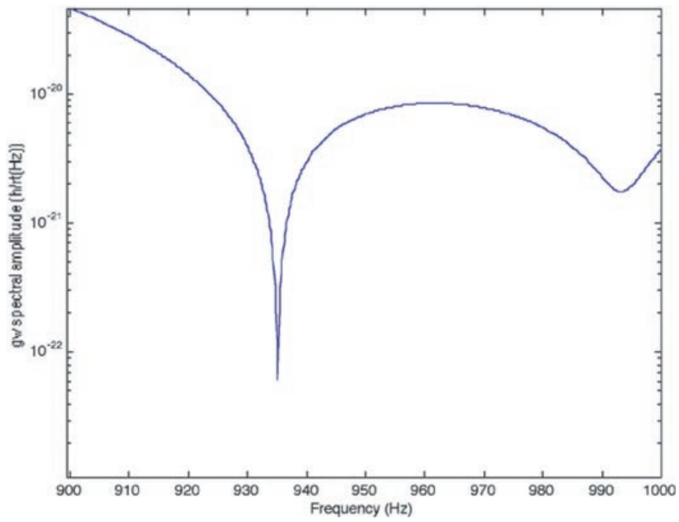

Figure 4. The predicted new experimental strain sensitivity of the NAUTILUS.

If we consider a sinusoidal wave of amplitude h_0 and frequency f_g, constant for the entire observation time t_m, the Fourier transform amplitude at f_0 is $\frac{1}{2}h_0t_m$ with a bandwidth given by t_m^{-1}. Then the SNR on resonance can be written as

$$\mathrm{SNR} = \frac{\frac{1}{2}h_0^2t_m^2}{S_h(f_0)}. \tag{3}$$

The detection of a continuous signal of known frequency places different requirements with respect to the strategy for burst detection. In the former case, one does not need a large bandwidth, and consequently the requirement on the antenna–transducer coupling is less severe than in the burst detection case. The effort must be focused on achieving the lowest possible value of the factor T/Q.

The value of h_0 from the signal of the pulsar in SN1987A, detectable with SNR = 1, is $h_0^{\min} = 4.7 \times 10^{-26}$ at 935 Hz. This value can be reached with a peak strain sensitivity of 6×10^{-23} Hz$^{-1/2}$, by integrating the signal for 1 month. Such unprecedented sensitivity can be achieved in principle with the NAUTILUS.

Some very stringent conditions must be fulfilled; in particular the high inherent quality factor of the bar (of the order of 10^7) should be preserved. This is not easy, because the bar is actually coupled to two other oscillators, exhibiting lower quality factors: the resonant transducer and LC electrical oscillator (formed by the capacitance of the transducer and the inductance of the superconducting transformer). It is therefore convenient to have a low coupling among these oscillators.

The sensitivity that can be achieved is shown in figure 4: the parameter values we assumed for this calculation are typical of devices which have already been tested in our laboratories: the rosette type capacitive transducer, a superconducting transformer of relatively high Q (7×10^5) and a commercial quantum design dc SQUID. In this example, the bar and transducer are not perfectly tuned: the bar frequency is 937 Hz (requiring a new cylindrical bar, 10 cm shorter than the present one) and transducer frequency is 1044 Hz. The resulting sensitivity at the lowest mode frequency (935 Hz) turns out to be much better than at the other modes. If a factor T/Q as low as 10^{-8} is reached, the strain sensitivity at 935 Hz reaches 6×10^{-23} Hz$^{-1/2}$.

This is what we hope and plan to achieve in the next science run of the NAUTILUS.

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