ROG

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1 Introduction

The ROG group is currently operating the cryogenic gravitational wave (GW) bar detector NAUTILUS, hosted in Frascati National Laboratory. The other detector that was operated by the ROG group, EXPLORER at CERN, ceased its operation on June 2010, by decision of INFN. The main goal of this search is the direct detection of the GW's that could be emitted by astrophysical sources (such as Supernovae or Coalescent Binaries). Such detection would be of enormous interest for general relativity and astrophysics.

The NAUTILUS detector consists of an aluminum cylindrical bar having a mass of $\simeq 2.3$ tons, with a capacitive resonant transducer mounted on one of the bar faces. It is contained in a vacuum cryostat, cooled at cryogenic temperatures (at present $\simeq 3$ K, but a temperature as low as 0.1 K can be reached) to reduce thermal noise, and isolated from seismic and acoustic disturbances.

The capacitive transducer is coupled to a very low noise superconducting amplifier (d.c. SQUID) whose output is acquired by a VME ADC board, sampled at 5 kHz.

A GW signal would excite the mechanical resonant modes of the bar-transducer system. When searching for impulsive signals, the data are filtered with an adaptive filter matched to a delta-like signal. This search for bursts is suitable for any transient GW which shows a nearly flat Fourier spectrum at the two resonance frequencies of the detector.

Both EXPLORER and NAUTILUS have been kept in continuous observational mode since 2003, with a duty cycle between 80 and 90%, mainly limited by the necessary periodic cryogenic operations.

The LNF group has major responsibilities in the maintenance and running of NAUTILUS (including the production of liquid Helium), in the maintenance, upgrading and running of the cosmic ray detectors, in the data acquisition and in many items of data analysis.

2 NAUTILUS and EXPLORER

The ultra-cryogenic detector NAUTILUS is operating at the INFN Frascati National Laboratory since December 1995. It is equipped with a cosmic ray detector based on a streamer tube assembly.

The present data taking started in 2003, with a new bar tuned at 935 Hz, where a pulsar, remnant of the SN1987A, is supposed to emit GW's, with a more sensitive readout chain (the same as for EXPLORER), and a new suspension cable, to provide a more stable position setting. At present, the temperature of the bar is 3.5 K and the resulting strain noise (the minimum detectable spectral density) is $\tilde{h} \simeq 1 \cdot 10^{-21} \, / \sqrt{Hz}$ around 935 Hz, and $\tilde{h} \leq 10^{-20} \, / \sqrt{Hz}$ over about 50 Hz. At the beginning of 2009, we discovered that some wide-band noise was due to a malfunctioning of the UPS system. After changing the UPS and some adjustments in the SQUID electronic chain, the noise temperature decreased down to less than 1 mK, corresponding to an adimensional amplitude of GW bursts $h \simeq 2.4 \cdot 10^{-19}$.

The EXPLORER antenna was located at CERN and was very similar to NAUTILUS. Also its duty cycle was very high (of the order of 90%), its noise temperature was about 2 mK, with a strain sensitivity $\tilde{h} \simeq 2 \div 3 \cdot 10^{-21} \ /\sqrt{Hz}$ around the two resonances at 904 Hz and 927 Hz, and $\tilde{h} \leq 10^{-20} \ /\sqrt{Hz}$ over about 30 Hz. EXPLORER was equipped with a cosmic ray detector, based on a set of long plastic scintillators.

The read-out systems installed in 2001 on EXPLORER and in 2003 on NAUTILUS, obtained a larger bandwidth and consequently improved the time resolution (a few ms), as it is also been checked with the events due to cosmic ray showers.

In the last years a continuos effort has been paid in improving the data analysis system already present and in testing independent algorithms and new methods. As a result of these, still going, efforts we were able to improve the accuracy in the reconstruction of both the amplitude and time characteristic of the signals. At the same time, we performed detailed studies of the detectors response to other class of signals than the simple delta-like burst previously considered. All this was done also with a particular eye on the perspective of performing joint analyses with the interferometric type of GW detectors, which do have a much better sensitivity than the resonant bar detectors, but up to now have suffered from very long interruptions in their operation. At present, both the US interferometers (LIGO) and the french-italian one (VIRGO) are down for a major upgrade that will remain inoperative for at least 4 years, leaving the INFN bar detectors (AURIGA and NAUTILUS) the only continually operational GW detectors.

2.1 Analysis of EXPLORER-NAUTILUS data

We continued to study all possible wide-band noises that can result in a candidate event and also, through simulations and software injections of signals, to find the event characteristics (e.g. length vs. amplitude) that an event due to a real excitation must have. All this was used to reduce the number of candidate events by putting vetos on periods or single events with understood instrumental noise excess, in addition to the usual vetos on events triggered by cosmic rays showers.

In 2010, up to the EXPLORER shutdown in June 10^{th}, we had a total of $\simeq 113$ days of good data periods in the overlap between EXPLORER and NAUTILUS.

We have finished the analysis of the last period of NAUTILUS- EXPLORER overlapping operations, from April 2007 to June 2010. The analysis of this period of data, about 3 years long, was performed improving the methods used in the past, including a detailed study of the efficiencies of both detectors through the use of software injections. The search for coincidences of possible delta-like excitations, at the level of 0.1 accidentals expected in the whole period, produced a null result. We produced upper limits on the rate of GW short signals impinging on the Earth, also in this case with more refined techniques, including optimization procedures at each amplitude. The computed upper limits, at least in the high-amplitude range, are the lowest ever produced, and in all ranges improved the results previously published by resonant detectors. A paper with this analysis have been submitted for publication [1)].

2.2 Other types of analyses

- Cosmic Rays - The study of the response of our detectors to cosmic ray showers continues to demonstrate experimentally the actual capability to detect very small mechanical excitations of the bars. While the study of the timing characteristics of the larger events produced by the rare very high density showers allows us a real measure of the accuracy in the time reconstruction, the study of the much more numerous cases of low density showers, performed with a cumulative-type analysis, constitutes an independent cross-check of the amplitude response calibration.

- Exotic particles - We continued the studies for exotic particles impinging on Nautilus or Explorer. Such particles could be with a quark "s" (nuclearites) and particles with only gravitational

interactions.
- Astrowatch - Since the large interferometric GW detectors (LIGO, Virgo) have suspended operations for major upgrades, in the next 3-4 years the only continually operating GW detectors will be NAUTILUS and AURIGA, at Legnaro National Laboratory. The two groups have reached an agreement to be in a coordinated "astrowatch operation". The intent is to be ready for a common data analysis in case an important astrophysical event (that is an event thought to be a source of GW radiation) would happen. This would lead to at least the establishment of an upper limit on the amount of GW delivered by the event, or, in the most optimistic case, if the data would show a clear behavior above any reasonable possibility of a noise fluctuation and in agreement with the expectations for that event, to a claim for detection.

In 2012, the interferometric detector GEO (Hannover, Germany) has joined this agreement for astrowatch operation. GEO operations is not continuos, being on mainly on weekends and nights, since its main operation is devoted to upgrade and operational studies.

3 List of Conference Talks by LNF Authors in Year 2010

1. F. Ronga, Vulcano workshop 2012 - Frontier objects in astrophysics and particle physics. Vulcano (Italy)

4 Publications

References

1. P. Astone *et al.*, "Analysis of 3 years of data from the gravitational wave detectors EXPLORER and NAUTILUS", arXiv:1212.5202 [gr-qc].

2. M. Bassan *et al.*, "Measurement of the thermal expansion coefficient of the Al 5056 alloy in the $0.3 < T < 2$ K temperature range", arXiv:1212.0368 [cond-mat.mtrl-sci].

3. M. Bassan *et al.*, "Vibrational excitation induced by electron beam and cosmic rays in superconductive aluminum bars", J. Phys. Conf. Ser. **375** (2012) 062006 (arXiv:1105.4724 [gr-qc]).

4. F. Ronga, "Analysis of the MACRO experiment data to compare particles arrival times under Gran Sasso", arXiv:1208.0791 [hep-ex].