EXPLORER and NAUTILUS gravitational wave detectors: a status report

2008 Class. Quantum Grav. 25 114048

(http://iopscience.iop.org/0264-9381/25/11/114048)

Class. Quantum Grav. 25 (2008) 114048 (8pp) doi:10.1088/0264-9381/25/11/114048

EXPLORER and NAUTILUS gravitational wave detectors: a status report

P Astone[1], R Ballantini[2], D Babusci[3], M Bassan[4,5], P Bonifazi[1,6], G Cavallari[7], A Chincarini[2], E Coccia[4,8], S D'Antonio[5], M Di Paolo Emilio[8,9], V Fafone[4,5], S Foffa[10], G Gemme[2], G Giordano[3], M Maggiore[10], A Marini[3], Y Minenkov[8], I Modena[8], G Modestino[4,5], A Moleti, G V Pallottino[1,11], R Parodi[2], G Pizzella[3,4], L Quintieri[3], A Rocchi[5], F Ronga[3], R Sturani[10], R Terenzi[5,6], G Torrioli[1,12], R Vaccarone[2], G Vandoni[7] and M Visco[5,6]

[1] INFN, Sezione di Roma, Roma, Italy
[2] INFN, Sezione di Genova, Genova, Italy
[3] INFN, Laboratori Nazionali di Frascati, Frascati, Italy
[4] Dip. Fisica, Università di Roma 'Tor Vergata', Roma, Italy
[5] INFN, Sezione di Roma Tor Vergata, Roma, Italy
[6] INAF, Istituto Fisica Spazio Interplanetario, Roma, Italy
[7] CERN, Geneva , Switzerland
[8] INFN, Laboratori Nazionali del Gran Sasso, Assergi, L'Aquila, Italy
[9] Università dell'Aquila, Italy
[10] Dep. de Phys. Théorique, Université de Genève, Genève, Switzerland
[11] Dip. Fisica, Università di Roma 'La Sapienza', Roma, Italy
[12] CNR, Istituto di Fotonica e Nanotecnologie, Roma, Italy

Received 8 January 2008, in final form 17 April 2008
Published 15 May 2008
Online at stacks.iop.org/CQG/25/114048

Abstract
The two cryogenic resonant bar detectors of the ROG Collaboration, EXPLORER and NAUTILUS, have been taking data continuously with a high duty cycle for several years. We report here on the status of recent analysis of the data and in particular on the results of the burst searches in the year 2004.

PACS numbers: 04.80.Nn, 95.55.Ym

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

1. Introduction

The ROG Collaboration has been operating two cryogenic gravitational wave (GW) bar detectors: EXPLORER (at CERN, Geneva, Switzerland) and NAUTILUS (at the INFN Frascati Laboratory, near Rome, Italy) [1–3].

Both detectors consist of an aluminum cylindrical bar with a mass of $\simeq$2.3 tons, with a capacitive resonant transducer mounted on one of the bar faces. They are contained in a vacuum cryostat, cooled at cryogenic temperatures ($\simeq$3 K) to reduce thermal noise, and

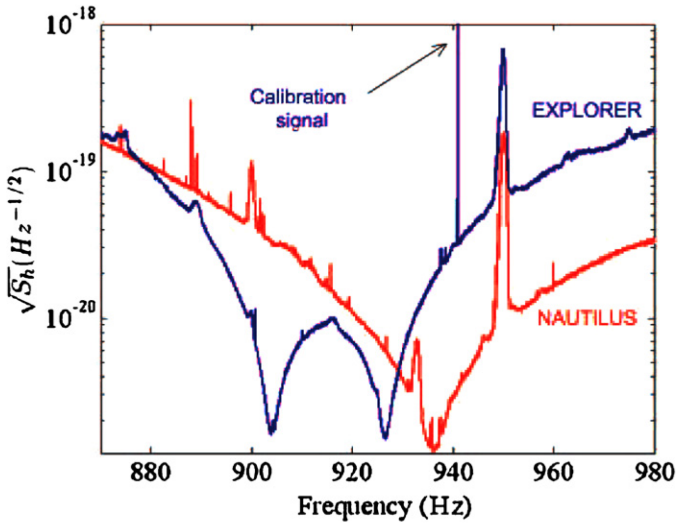

Figure 1. Typical present sensitivity curve for EXPLORER and NAUTILUS detectors.

are isolated from seismic and acoustic disturbances. The capacitive transducer is coupled to a very low noise superconducting amplifier (dc SQUID) whose output is acquired by an analog-to-digital converter board, sampled at 5 kHz.

The ultra-cryogenic detector NAUTILUS is operating at the INFN Frascati National Laboratory since December 1995 [2]. It is equipped with a cosmic ray detector based on streamer tube technology [6]. NAUTILUS showed a capability of reaching a temperature as low as 0.1 K, being equipped with a ^{3}He–^{4}He dilution refrigerator. This ultra-cryogenic operational mode would result in a better sensitivity but also in a decrease of the duty cycle. Priority was given to the observational time and so we keep the standard operation at about 3 K. The resulting strain spectral noise has a minimum $\tilde{h} \simeq 1 \times 10^{-21}$ Hz$^{-1/2}$ around 935 Hz, and $\tilde{h} \leqslant 10^{-20}$ Hz$^{-1/2}$ over a bandwidth of about 30 Hz. Integration over this bandwidth yields the minimum detectable pulse energy or noise temperature less than 2 mK. This corresponds to a conventional (1 ms) amplitude of GW bursts $h = 3.4 \times 10^{-19}$.

The EXPLORER antenna, in operation at CERN since 1986, is very similar to NAUTILUS, and works at a fixed temperature of 2.6 K. Its noise temperature is of about 2 mK, with a minimum spectral strain sensitivity $\tilde{h} \simeq 2 \times 10^{-21}$ Hz$^{-1/2}$ around the two resonances at 904 Hz and 927 Hz, and $\tilde{h} \leqslant 10^{-20}$ Hz$^{-1/2}$ over a bandwidth of about 30 Hz. Also EXPLORER is equipped with a cosmic ray detector, based on a set of long plastic scintillators.

NAUTILUS has been kept in continuous observational mode since May 2003, and EXPLORER since March 2004, both with a duty cycle close to 90%, mainly limited by the periodic maintenance operations: normally 1 day for refilling of cryogenic fluids every 3 weeks. Data taking also continued over Christmas holidays, despite the shut down of the respective laboratories. Thanks to the read-out systems installed in 2001 on EXPLORER and in 2003 on NAUTILUS, the detectors obtained a larger bandwidth with respect to the past runs [4].

In April 2006, we changed the bias voltage in the transducer of EXPLORER: this moves the resonant frequencies of the coupled system bar + auxiliary oscillator by a few hertz. Even if there is not a significant improvement of the strain sensitivity, it results to be more symmetric (see figure 1).

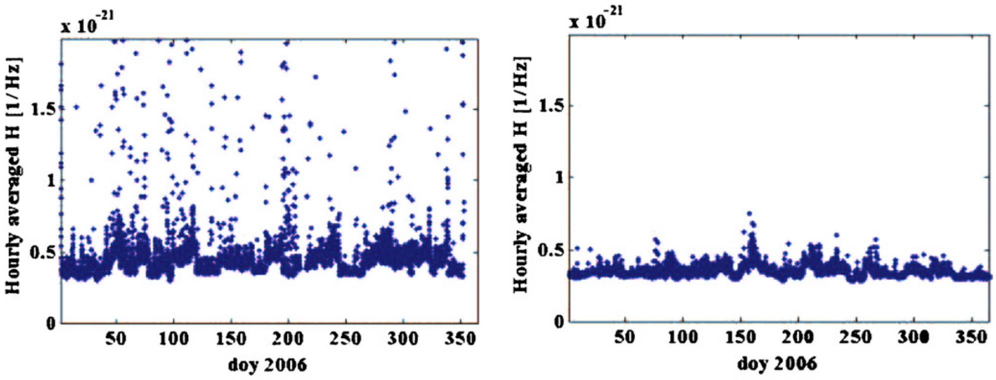

Figure 2. The noise level, averaged over 1 h, in the whole year 2006, for EXPLORER (left) and NAUTILUS (right).

We report here a summary of results of recent analysis. We include here the results of the search for GW bursts performed in the year 2004 and, at the light of these, we discuss the interest in continuing the observations in future.

2. Data quality and calibration

Our detectors show a response in good agreement with the model. The main parameters of the model were measured by laboratory tests on the single components of the detectors. Hardware injections are used as a powerful tool to verify and perfectly tune the model and to control the filters response. Software injections are largely applied in order to test new filters both for delta-like bursts and other classes of signals [5].

The behavior of the detectors has been very stable for years. We illustrate this by considering the behavior of the detectors in the last year. In figure 2 we show, for each detector, the noise level hourly averaged, during 2006, expressed in units of $H(\omega)$ (Hz^{-1}), the Fourier transform of the pulse at the antenna frequency. Histograms of these noise levels are reported in figure 3. We see that both detectors were practically for all the year at a sensitivity $H(\omega) \leqslant 10^{-21}\ \mathrm{Hz}^{-1}$.

The cryogenic resonant GW detectors EXPLORER and NAUTILUS are able to detect cosmic ray showers [7]. The cosmic ray detectors were originally installed as veto systems, but turned out to be an original tool to study the response of the antennas: indeed, a cosmic ray shower produces in the bar a real mechanical excitation, probably the closest to a pure delta signal.

The excellent timing resolution of the shower detectors (better than 0.1 ms) has allowed us to study in great detail the timing in the response of antennas and filters. In figure 4 we show, for instance, the time delay between EXPLORER events and cosmic ray signals, together with a Gaussian fit.

These results contributed to our choice of the coincidence window $\Delta t = 30$ ms for the EXPLORER–NAUTILUS coincidence search, including the delays due to systematics, time of flight and other possible offsets. Cosmic rays can also be used for further controls on amplitude calibration of the detectors for delta-like pulses, independent from the hardware calibrators commonly used for hardware injections. A thermoacoustic model has been shown to be able to describe the amplitude of the excitations produced by cosmic rays within a 20% of uncertainty [8].

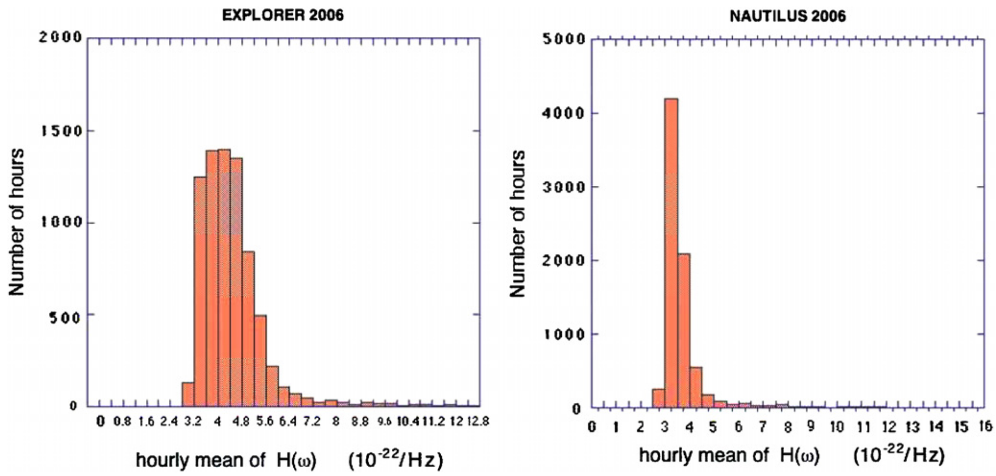

Figure 3. Histograms of the noise level of EXPLORER and NAUTILUS, averaged over 1 h, in the year 2006.

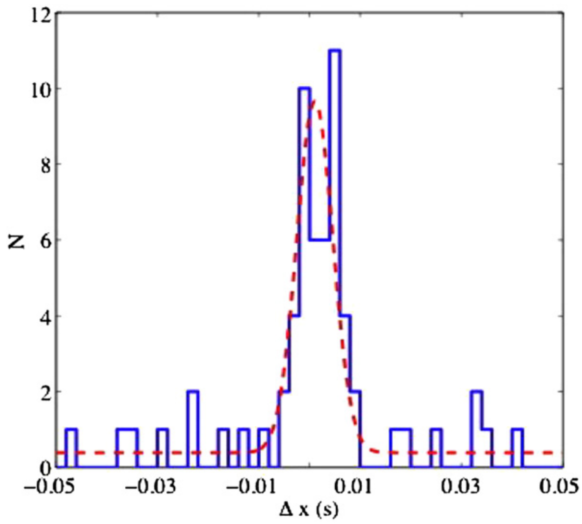

Figure 4. Distribution of time differences between events in coincidence at the antenna output (EXPLORER) and in the cosmic rays detector. We expected for the coincidences a Gaussian distribution over a flat background due to noise not correlated to the cosmic rays events. The Gaussian fit yields for the coincidences an average instrumental systematic delay $\Delta t_0 = 1.3$ ms and a standard deviation (on a single detector) $\sigma = 3.6$ ms.

3. Data analysis

The main subject of our analysis is the search for GW bursts. The data are filtered with an adaptive filter matched to delta-like signals for the detection of short bursts [9]. 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. In the last few years, a continuous effort has been made to improving the data analysis system already present and in testing independent algorithms and new methods. As a result of these, still ongoing, efforts we are 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 classes of signals than the simple delta-like burst previously considered. All this was done also with the perspective of performing joint analyses with the interferometric GW detectors.

3.1. EXPLORER–NAUTILUS coincidences

The analysis of correlations and coincidences between the outputs of EXPLORER and NAUTILUS is an ongoing project of our collaboration, with periodic updates [10–12]. In particular, analyses relative to the data gathered by both detectors in the science runs of 2001 have been debated because of an intriguing coincidence excess [13]. The results of the 2003 science run [12] excluded the interpretation of the 2001 results in terms of continuous and uniform (in time) arrival of burst signals. The interest of these analyses for understanding possible correlations in the background of two GW detectors cannot be overestimated as it can reveal unpredicted or underestimated sources of noise. On the other hand, the presence in our long runs of coincidence excesses and of some clustering of the events during short period of time cannot exclude the existence of a nearby (within 100 pc) compact object acting as a GW bursters which may be active for periods of the order of a few days and silent for periods of several months. This kind of source can be considered in our opinion the only possibility for detecting GW with present bar detectors (apart from the rare galactic supernova). We find that this theoretical possibility has not yet been excluded by any data today and adds further interest to the analyses of long periods of data.

We report here the results of the search for GW bursts in 2004 using the same criteria used for the analysis of 2003 [12, 14]. In particular the threshold for the determination of the events is maintained at 19.5 in energy signal-to-noise ratio and the coincidence window is fixed at 30 ms, maintaining in this report the same analysis conditions as used in 2003.

In 2004 we had a total overlap of 216.5 days of good data periods for both EXPLORER and NAUTILUS. We have 50 464 EXPLORER events and 66 756 NAUTILUS events, with average values of the noise temperatures $\langle T_{\mathrm{eff}}\rangle = 2.788$ mK for EXPLORER and $\langle T_{\mathrm{eff}}\rangle = 1.79$ mK for NAUTILUS. We found 13 coincidences against an average number of accidentals of 10.7 in a Poissonian distribution. The distributions in sidereal time of the coincidences and of the accidentals are shown in figure 5 binned in 1 h bins. For the calculation of the sidereal hour we used here the Greenwich mean sidereal time (GMST). The number of accidental coincidences is estimated by shifting the data stream of one detector with respect to the data stream of the other one by 100 steps of 2 s and measuring the average number of coincidences in each 1 h bin.

As already discussed in [12], it is interesting to investigate how the coincidences are distributed during the year 2004. We report the coincidences during 5 day periods in figure 6. Most of the coincidence excess in 2004 is concentrated in the time interval days 205–215.

3.2. IGEC-2 collaboration

Since 2005, both the ALLEGRO detector at LSU (USA) and AURIGA at INFN Legnaro Labs have resumed regular operation: therefore we have restarted the IGEC Collaboration under a new agreement (IGEC-2) between the four bar detectors. As a first product of this agreement, 6 months of data (May–November 2005) were searched for triple coincidence

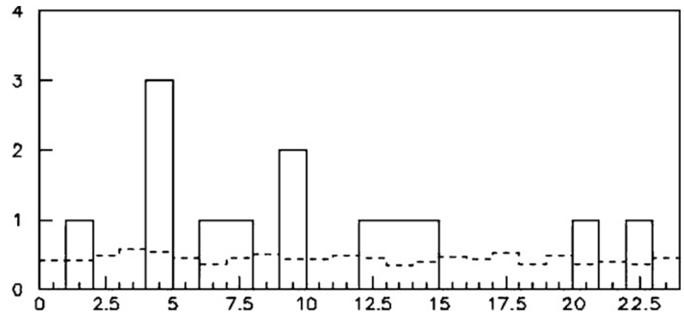

Figure 5. EXPLORER–NAUTILUS coincidences in 2004. Number of coincidence and average accidentals (dashed) as a function of sidereal hour.

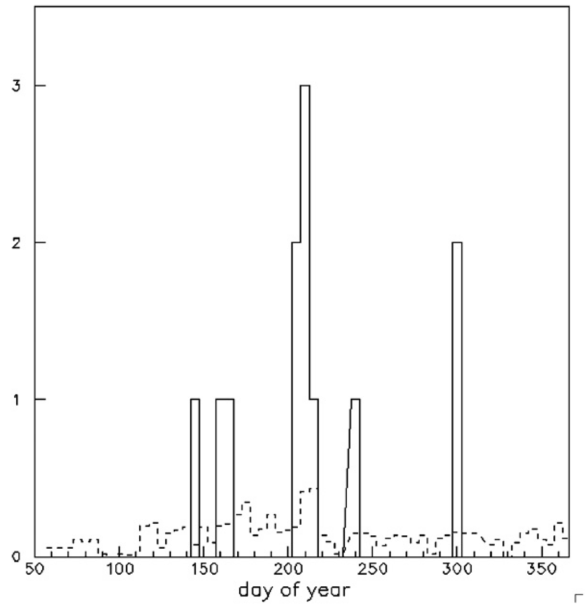

Figure 6. Coincidences and accidentals in 2004 for 5 day periods.

(the ALLEGRO data are kept for further analysis in the case of positive results). A very low threshold of accidental rate was set, namely one per century, and no triple coincidence was found. Detailed results of this search will be published soon [15] and are presented at this conference by F Salemi. A new analysis, covering data of all 2006, is in progress.

3.3. Collaborations between resonant bars and interferometers

A first joint data analysis between all the INFN GW detectors (AURIGA, EXPLORER, NAUTILUS and VIRGO) has been performed for the period of the VIRGO C7 run (September 2005). Since the period of exchanged data was very short, the analysis has addressed more methodological than scientific issues [16]. The efficiency of each detector separately, and then of the network, was extensively studied through a large number of software injections of damped sinusoid signals.

3.4. Other type of analyses

3.4.1. Search for periodic signals. We also continued analysis of monochromatic signals [17], both with the already tested coherent algorithms and a new non-coherent one, currently under test (see the contribution of S Foffa at this conference). A non-coherent search is in principle less sensitive than a coherent one: however, being much faster, it allows us to analyze, for a given computing time and power, amounts of data more than 100 times larger, thus providing at the end a better overall sensitivity.

3.4.2. Triggered search. The analysis of our data at the times of a large number of gamma-ray bursts allowed us to set upper limits on the amplitude of possible GW signals associated with them [18]. This kind of study is continuing and has been extended to detailed analysis of the data collected in coincidence with some rare astrophysical events, such as the giant flare of December 2004 (work in progress). This kind of analysis constitutes a further motivation for studying new algorithms for correlating data of two or more detectors (see the contribution of R Sturani and R Terenzi at this conference).

3.4.3. Cosmic rays. The cryogenic resonant GW detectors EXPLORER and NAUTILUS are able to detect cosmic ray showers [7]. The experimental result leads one to classify the responses in two categories: many small signals, in most cases with small multiplicity, obeying the thermoacoustic model, and few large signals, usually associated with large multiplicity, which exceed the thermoacoustic model by orders of magnitude, and whose understanding is still under investigation with the RAP experiment at LNF [8]. 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.

Acknowledgments

We thank F Campolungo, G Federici, M Iannarelli, R Lenci, R Simonetti, F Tabacchioni, E Turri and the LNF and CERN Cryogenic Services for their technical support.

References

[1] Astone P *et al* (ROG Collaboration) 1993 *Phys. Rev.* D **47** 362
[2] Astone P *et al* (ROG Collaboration) 1997 *Astropart. Phys.* **7** 231
[3] Astone P *et al* (ROG Collaboration) 2006 *Class. Quantum Grav.* **23** S57
[4] Astone P *et al* (ROG Collaboration) 2003 *Phys. Rev. Lett.* **91** 111101
[5] Astone P *et al* 2006 *J. Phys. Conf. Ser.* **32** 192
[6] Coccia E *et al* 1995 *Nucl. Instrum. Methods* A **335** 624
[7] Astone P *et al* 2000 *Phys. Rev. Lett.* **84** 14
Astone P *et al* 2001 *Phys. Lett.* B **499** 16
Astone P *et al* 2002 *Phys. Lett.* B **540** 179
[8] Bassan M *et al* 2006 *Europhys. Lett.* **76** 987

[9] Astone P, Buttiglione C, Frasca S, Pallottino G V and Pizzella G 1997 *Nuovo Cimento* **20** 9
[10] Astone P *et al* (ROG Collaboration) 2002 *Class. Quantum Grav.* **18** 243
[11] Astone P *et al* (ROG Collaboration) 2002 *Class. Quantum Grav.* **19** 5449
[12] Astone P *et al* (ROG Collaboration) 2006 *Class. Quantum Grav.* **23** S169
[13] Astone P *et al* (ROG Collaboration) 2003 *Class. Quantum Grav.* **20** S785
[14] Pizzella G 2007 *Frontier Objects in Astrophysics and Particle Physics* ed F Giovannelli and G Mannocchi vol 93 (Bologna: Italian Physical Society) p 67
[15] IGEC2 Collaboration 2007 *Phys. Rev.* D **76** 102001
[16] AURIGA, ROG and Virgo Collaborations *Class. Quantum Grav.* submitted
[17] Astone P *et al* (ROG Collaboration) 2006 *Class. Quantum Grav.* **23** S687
[18] Astone P *et al* (ROG Collaboration) 2005 *Phys. Rev.* D **71** 042001