INITIAL OPERATION OF THE GRAVITATIONAL WAVE DETECTOR AURIGA

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The resonant g.w. detector AURIGA began to take data last May at the INFN Laboratori Nazionali di Legnaro. The typical noise temperature of the detector is 7 mK and its effective bandwidth is about 1 Hz. For more than two thirds of the time its noise temperature stays below 14 mK. The cryogenic operation has been stable since February and the working temperature of the bar is typically about 0.2 K. The quality factors of the bar+transducer modes are respectively 2.4 and 3.2 millions for the 911 and 929 Hz resonances, with a bias field in the capacitive transducer of 5.4 MV/m. The sensitivity of the detector is currently limited by the noise performance of the transducer-amplifier chain; in fact, the back action is dominating over the mechanical brownian noise and increases the effective temperatures of the modes at about 1 K. We briefly present also the perspectives for future developments.

1 Introduction

The resonant bar detector AURIGA [1] has recently started full operation at the Laboratori Nazionali di Legnaro of the Istituto Nazionale di Fisica Nucleare. The antenna is an Al5056 bar of about 2.3 *tons* and is equipped with a

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resonant capacitive transducer coupled to a d.c.SQUID through an impedance matching transformer. A second capacitive transducer is provided on the bar for calibration purposes and is not in resonance with the sensitive mechanical modes. An internal cryogenic switch on the transducer output can select between the internal SQUID amplification chain and an external port, where an auxiliary dewar could house an alternative SQUID chain. The liquid Helium cryostat houses a $^3He -^4 He$ dilution refrigerator whose mixing chamber cools both the bar and the inner radiation shield. The other radiation shields are cooled by the 1K pot, the He main bath and He vapour. The mechanical suspensions consist of a room temperature stage made by rubber disk stacks loaded by lead masses and of a series of cryogenic stages made by rods and ring-shaped masses (Fig.1). The rods are four per each stage and have been equally tensioned during assembling. The ring shaped masses support the various cryogenic stages. The bar is suspended by a belly cable suspension which provide also for the thermal link, as in the NAUTILUS detector.[2]

Elsewhere in these proceedings, Vedovato et al.[3] describe the fast data acquisition system, its synchronization to UTC and the data analysis procedures.

In the previous cool down of the detector[4] from mid 1995 to mid 1996, we tested the performances of the cryogenics, of the mechanical suspensions and of the data acquisition system. The transducer output was monitored through the room temperature port either to calibrate the detector or to measure the antenna noise by means of FET amplifiers. The results obtained at liquid Helium temperature were satisfactory in many respects, in particular for the attenuation of the mechanical suspensions, the calibration procedure, the data acquisition and the antenna noise performance, which has been thermal over a long time span at about $6K$. Unfortunately, a crucial cryogenic problem forced the run to stop and prevented us from testing the noise performance of the detector at lower temperatures with the d.c.SQUID amplifier. In fact, the pipeline which was provided inside the cryostat to refill the 1K pot of the dilution refrigerator began to plug frequently due to condensation of impurities. We fixed this problem by using a low loss transfer tube from the main bath of the cryostat, since it can be easily removed and cleaned.

The present run of the detector has shown a stable cryogenic operation with the dilution refrigerator since February 1997. The operating temperature of the bar and transducer has been lowered to about $90mK$ and is been usually kept at about $0.2K$. Since the last week of May we succeeded in stabilizing the noise temperature of the detector to about $7mK$, as discussed in the following section. This achievement required some work on the electrical configuration of the detector and a search for suitable electric bias fields in the signal and calibrating transducers. In fact, the magnitude of the biases shifts the frequen-

Figure 1: inner part of the AURIGA cryostat before the final assembly of the transducer and the thermal shields. It shows the bar, the inner stages of the suspensions made by ring-shaped masses and elastic rods, and the toroidal liquid Helium tank.

cies to an extent which can affect the tuning of the bar+transducer modes with other internal resonances of the detector whose origin is still unknown.

Up to now, we are not yet monitoring ambient disturbances such as vibrations, electromagnetic fields and cosmic rays. In the first months of full operation, we found that the major source of disturbance is 1K pot refilling, which blinds the detector during the few hours needed for completing it. On the contrary, we have not found significant worsening of the noise temperature correlated to activities such as refilling of the Helium main bath or usual human activities in the laboratory. At this stage however, we cannot yet comment on the relationship between ambient disturbances and measured signals above some threshold.

In the following Section we discuss the performances of the AURIGA detector during the first two months of operation, in particular for what concerns the noise characteristics, the evidence of back-action noise and the calibration procedure. Some perspectives for future improvements of the detector are presented in Sect. 3.

2 Experimental Results

2.1 Experimental Configuration

The position of the detector as measured by the GPS receiver is $44°21'12''$ N, $11°56'54''$ E at sea level. The azimuth of the bar axis is $44°$. It is perpendicular to an earth great circle which goes across Italy, Louisiana and Australia, so that ALLEGRO, AURIGA, EXPLORER, NAUTILUS, and NIOBE are almost parallel.

The AURIGA signal readout scheme is based on a capacitive transducer with a resonating plate of $\simeq 0.3$ Kg effective mass, mushroom shaped and tuned to the bar first longitudinal mode within $\simeq 2$ Hz. The gap between plates is $\simeq 80$ μm, the capacitance is 2.7 nF and the electric field bias is 5.4 MV/m. A twisted pair of NbTi wires connects the transducer to the dc decoupling capacitor and the impedance matching transformer. These are housed in a superconducting shield suspended near the central section of the cryostat from the second ring-shaped mass (Fig. 1). The twisted wires are first glued to the edge of the bar end face, then to a support close to the bar central section and to the inner two ring-shaped masses, for a total length of about 2.5 m. Before entering the impedance matching transformer, a cryogenic switch is provided for selecting either the internal transformer and the SQUID chain or a path to an external port. In all the measurements performed in this run the internal transformer and SQUID chain has been selected. The primary inductance of the transformer is $\simeq 5$ H and the electrical resonator made by this coil and the transducer capacitance is currently not tuned to the mechanical modes. The secondary inductance is 2.5 μH and is part of a standard superconducting transformer to the SQUID. The coupling between the primary and the secondary is estimated to be $K \sim 0.76$. The d.c.SQUID is a standard Quantum Design sensor with a 1.86 μH input coil, coupled with a measured mutual inductance of 10.4 nH. The SQUID is connected to the room temperature electronics by a non standard long cable, which provides also for wires thermalizations. The operating temperature of the impedance matching stage and the SQUID is about 0.5 K.

The frequencies and quality factors of the bar+transducer mechanical modes are respectively $\nu_- = 911.75\ Hz$, $Q_- = 2.4 \times 10^6$ and $\nu_+ = 929.84\ Hz$, $Q_+ = 3.2 \times 10^6$. From the stability of the frequencies over two months the leakage of the transducer bias is estimated $\simeq 0.1\ V/month$. The SQUID amplifier dynamic input impedance does not affect the mechanical $Q_\pm$ values. This has been checked in two ways: i) by observing that $Q_\pm$ are well reproducible for bias electric fields at the transducer as low as $0.6\ MV/m$; ii) by measuring the $Q_\pm$ dependence on SQUID bias current and open loop gain.[5]

The cryogenic operation of the detector requires about one refill per week of the liquid Helium main bath and one refill every $\simeq 50\ h$ of the 1 K pot of the dilution refrigerator. The refills typically last about 6 and 3 hours respectively. The total liquid Helium consumption is about $100\ liters/day$. The operating temperature of the bar is $\simeq 240\ mK$, obtained with a low ^{3}He flow rate through the refrigerator, $\sim 200\ \mu mol/s$.

2.2 Noise Performance

The data has been analyzed with the Wiener filter for δ-like signals in a $70\ Hz$ bandwidth around the modes.[3] The noise temperature of the filtered data, i.e. the minimum detectable energy at Signal to Noise Ratio $SNR = 1$, is shown in Fig.2 for the first four weeks of operation. The noise temperature reaches $7\ mK$ and stays below $14\ mK$ for more than 2/3 of the time, including the interruptions devoted to detector calibration. The only operation which has a substantial effect on the noise temperature is the 1 K pot refill; in fact the detector becomes practically blind during the whole duration of the operation. No other correlation with usual laboratory activities is evident up to now. A sample of the gaussian statistics of the amplitude output is shown in Fig.3a: the minimum detectable Fourier transform of the gravitational wave strain amplitude at input is $H(\omega) \simeq 4.5 \times 10^{-22} Hz^{-1}$, bilateral. The spectral power density of strain noise at input of the bar shows two minima values of $\simeq 6 \times 10^{-22} Hz^{-1/2}$, with a total effective bandwidth of $\simeq 0.9 Hz$ (Fig.3b).

The present noise performance is limited by the transducer-amplifier chain. In fact, the lock-in analysis shows that the noise energies in both modes are substantially greater than the brownian level, $\sim 1\ K$, even though their statistics is Boltzmann. This back-action noise source is not yet throughfully understood. The wide band noise of the SQUID output is $\simeq 8 \times 10^{-6}\ \Phi_0/Hz^{-1/2}$, bilateral, a figure which is greater than what we previously measured on bench tests.

For what concerns the δ-like events search we found a slight excess of counts as compared to a Monte Carlo prediction (Tab.1). This excess is reduced after applying a χ^2 veto [6], that is a consistency statistical test which discriminates

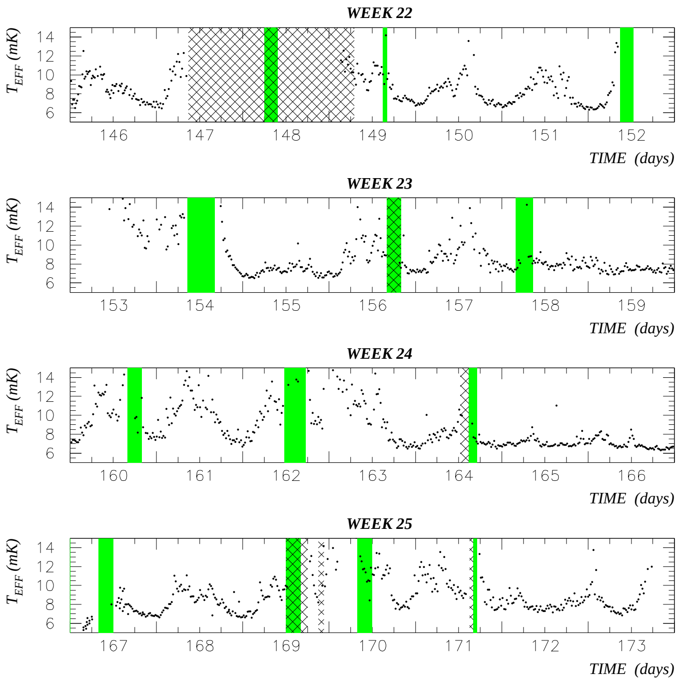

Figure 2: Noise temperature for bursts of the AURIGA detector for the first four weeks of full operation in 1997. Each point is a 20 min average. Noise temperature is below 14 mK for more than 70% of the time. Grey shades refer to 1 K pot refills, grids to calibration procedures .

a δ-like mechanical excitation of the bar against other spurious signals such as those due to electromechanical sources. The veto we applied in Tab. 1 is still preliminary because the χ^2 time series is not stationary due to slight changes in time of the detector noise. However, at high SNR the χ^2 is mostly independent of the detector noise changes and so the veto becomes more efficient.

2.3 Detector Calibration

We developed a procedure to estimate the absolute energy sensitivity of the detector with the only assumption that our system is described by two coupled harmonic oscillators.[7] The procedure is based on the injection of a known

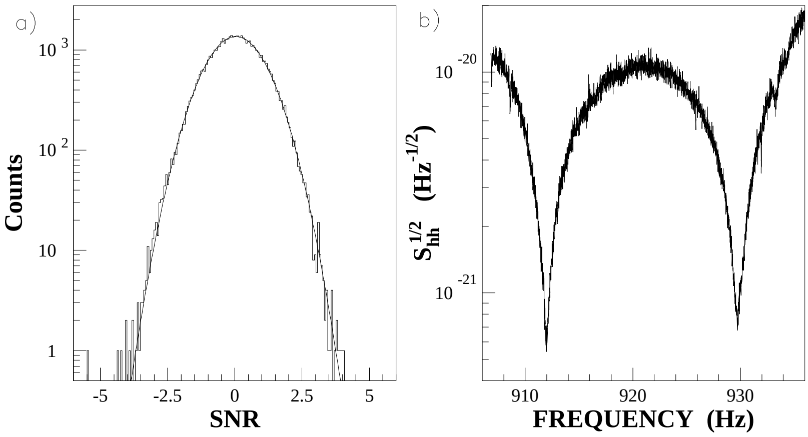

Figure 3: a) sample of gaussian statistics of the filtered data over 57 consecutive hours. $SNR = 1$ corresponds to a Fourier transform of the gravitational wave amplitude $H \simeq 4.5 \times 10^{-22} Hz^{-1}$. One count outside the SNR range is not shown. b) Square root of the bilateral spectral power density of strain noise at bar input averaged over two hours.

magnetic flux in the SQUID superconducting transformer through a calibrated mutual inductance.[1] The resulting back-action force excites the system resonances, each one described by 3 lumped elements (R_{eq},L_{eq},C_{eq}) at the SQUID input. The measured SQUID input current allows the estimate of all three electrical equivalent parameters and thus the absorbed energy. From the measurement of the SNR of a calibration pulse we obtain the noise temperature, T_{eff}. In addition the noise energy content of the modes in units of Boltzmann constant gives the modes equivalent temperature.

The wave amplitude calibration h requires two further generally accepted hypothesis: i) the bar equivalent mass is half of its inertial mass M_{bar}; ii) the relation between the gravitational force and the bar geometrical length L_{bar} is $F = M_{bar} L_{bar} \ddot{h}/\pi^2$.

3 Perspectives for Future Improvements and Conclusions

The recent operation of five resonant bar detectors with comparable sensitivities greatly improves the chances for a reliable detection of gravitational wave bursts. In fact, the agreement [8] among the experimental groups will soon allow a search for correlations in the detected signals above a given threshold. However, the present sensitivity is satisfactory only for the search of galac-

Table 1: sample of δ-like events search for the same 57 hours of data of Fig.3a. A χ^2 veto has been applied in a preliminary configuration and helps in reducing the excess measured over the Monte Carlo prediction for gaussian noise.

SNR	All AURIGA Events	Remaining after χ^2 Veto	Monte carlo Prediction
3÷4	31089	31065	27968
4÷5	3651	3645	2780
5÷6	101	100	46
6÷7	3	3	0
∼10	4	2	0
∼60	2	0	0

tic sources. Therefore, further substantial progresses in the short term rely mainly on the improvements in sensitivity, duty cycle and confidence of detection of the present network, as well as on the initial operation of the large interferometers.

3.1 Sensitivity and Duty Cycle

The AURIGA energy sensitivity to short gravitational waves bursts, as well as of other operating detectors, is presently limited by the noise performances of the transducer-amplifier chain to a level of the order of $10^4 \div 10^5$ $h\nu_0$ where ν_0 is the antenna resonance frequency. In fact, the numerical simulations of the noise performance of our detector show that the present ratio of mechanical quality factor over temperature, $Q/T \geq 10^7 K^{-1}$, is already well adequate for an overall energy resolution as good as $\sim$ 100 $h\nu_0$.[9] To fully exploit the potentiality of an ultracryogenic detector, the AURIGA collaboration is starting an R&D program devoted to the development of transducer-amplifier chains to approach this figure within a few years. In particular, we plan to realize in the short term a test facility for transducer-amplifier chains in order to test their noise performances at dilution refrigerator temperatures in configurations suitable for direct integration in present detectors. The facility will allow fast thermal cycles and will be equipped with suitable mechanical suspensions to keep the ambient vibrations at a negligible level. Work is in progress on resonant capacitive transducers of optimized mass, on SQUIDs coupled to high Q resonant loads [10] and on a new scheme of a Fabry-Perot cavity transducer. Both capacitive and optical chains are promising energy resolutions of the order of 100 $h\nu$: the former requires the realization of SQUID systems ready for integration at that level of performance [11], the latter relies on adapting and assembling already available components.

In addition to the development of transducer-amplifier chains, it is likely that the mechanical suspensions of the AURIGA detector will need to be improved too. In fact, the present performance of the suspensions is satisfactory as for the attenuation at the bar+transducer resonances of normal external vibrations, but there is evidence of mechanical resonances of suspension parts which are close to the modes and might limit the effective bandwidth of the detector as soon as the new transducers will be available. Moreover, to decrease the dead time of the detector due to cryogenic operations from the current level of $\simeq 10\%$ to negligible figures, some work is needed either to increase the mechanical attenuation from the 1 K pot stage to the bar or to cut significantly the turbulences related to 1 K pot refilling. The former would require the realization of new compact mechanical filters, the latter will be pursued in the near future by lowering the pressure of the main liquid He bath from which the pot is filled. We plan to start experiments also on the non linear behaviour of suspensions, in particular to estimate the up-conversion of low frequency seismic noise.

3.2 Confidence of Detection

In our opinion the confidence of bursts detection should not rely only on multiple coincidences in the output signals, but also on the measurement of specific features of the incoming wavefront. In fact, it is not clear at all how to estimate the background noise of coincidences, since at each detector the statistics of events above a given threshold cannot be taken as stationary. For this reason we took comparable commitment in recent years both on realizing the AURIGA detector itself and on developing and implementing specific capabilities [3] such as i) the measurement of arrival time of bursts with submillisecond resolution [12], ii) statistical tests of consistency with the signal expected shape [6], and iii) the solution of the inverse problem for a minimal network of bars which can provide measurements of specific properties of the Riemann tensor such as transversality and tracelessness.[13]

In particular, the high resolution measurement of arrival time is a powerful tool because it can allow to check for the propagation speed and the direction of the incoming wavefront, and sets as well more stringent requirements on the time window in which coincidences can be searched, from the current $\sim 1s$ to the time-of-flight of light between detectors. The effectiveness of signal absolute timing depends critically on the effective bandwidth of the detector and on the SNR; for instance, experiments show that $\simeq 18\ \mu s$ absolute timing is possible with a $\simeq 10\ Hz$ bandwidth and $SNR \simeq 10$.[12] At present, the effective bandwidths of the operating detectors are much smaller, $\sim 1\ Hz$, and therefore the capability of resolving the arrival time is limited in practice to a "phase" part which is given by $\sim 180\mu s/SNR$, superimposed on an uncertainty of an integer number of half the period of the antenna resonance, $0.5ms$ for a $1KHz$ detector. This uncertainty is proportional to SNR^{-1} and becomes negligible with respect to the "phase" part only for very high SNR. Even with this ambiguity, however, many advantages of the high resolution timing are still effective. In fact, for a couple of detectors operating at about the same frequencies, this ambiguity on measurement of delay times in detection just translates in more than one possible angle of incidence for the incoming gravitational wavefront with respect to the baseline between detectors. The number of angles will be limited to the maximum possible delay time divided by $\sim 0.5ms$; therefore, for a couple of nearby detectors such as AURIGA and NAUTILUS or AURIGA and EXPLORER the ambiguity is limited to two or three angles, since the baselines are respectively 397 and 455 Km. The intersection of the source locations as determined from each couple will leave only a few possible ones. For far away detectors, the number of such angles of incidence increases, so that at present only for very high SNR signals the timing would contribute to locate the source. However, the implementation of timing capability in the operating detectors to the level demonstrated by AURIGA would be a substantial improvement for the operating network. Moreover, timing is also a prerequisite for making any correlation of data among detectors to measure the gravitational wave properties and to solve the inverse problem.

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