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Developments in resonant-mass detectors

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Abstract
After a brief summary of the state of the art of resonant-mass detectors, we will describe the planned developments of bar antennas and the near-term perspectives related to the development of SFERA, a new, 33 ton, spherical detector.

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1. Introduction

Resonant-mass detectors are now in the continuous observational mode with a duty cycle near 100%. The five bar detectors distributed worldwide operated for a few years as a network, giving for the first time significant upper limits to the yearly rate of gravitational wave (GW) burst events in the Galaxy [1, 2].

Thanks to the upgrades of the read-out systems, a significant increase in the detection bandwidth has been achieved. The present spectral amplitude is $\tilde{h} \equiv \sqrt{S_h} \simeq 2 \times 10^{-21}\,\text{Hz}^{-1/2}$ with a bandwidth at the level of $10^{-20}\,\text{Hz}^{-1/2}$ up to 100 Hz [3] corresponding to a burst sensitivity $h \simeq 1.4 \times 10^{-19}$.

Developments in bar detectors can be achieved improving the read-out system and working at ultra-cryogenic temperatures, but much better sensitivities could be achieved by developing new acoustic detectors. The near future evolution of resonant detectors is considered in the direction of a sphere design: a sphere allows isotropic sky coverage, determination of the source direction and wave polarization. The needed technology is defined and is currently under test in MiniGRAIL [4] and Schenberg [5], the 68 cm diameter spherical detectors being developed at Leiden University and in Brazil. A report on the state of MiniGRAIL and Schenberg can be found in [6, 7]. The dual scheme [8, 9], proposed as the long-term evolution of resonant detectors, will give a further improvement in sensitivity and bandwidth and an R&D programme, already started, will answer in a few years about the detector feasibility. These evolutions of the current resonant antennas could permit these devices to complement, in specific frequency ranges, the interferometers, allowing a precise reconstruction of the gravitational wave signal.

In the following, we will summarize the most recent achievements in the read-out developments, the present status and near-term perspectives for bar detectors, and the main features of a larger and more sensitive sphere, proposed as the next step in the development of resonant detectors. A report on the state of the DUAL R&D can be found in [10].

2. Read-out developments

The mechanical oscillation induced in the antenna (made of a high Q material, at least of the order of 10^6) by interaction with the GW is transformed into an electrical signal by a motion or strain transducer and then amplified by an electrical amplifier. In the conventional scheme, resonant transducers matched to the resonant bar are used to enhance the displacement induced by the gravitational signal.

The sensitivity of the detector is limited by three sources of noise which, referred to the output are the narrowband thermal noise, due to the input wideband Brownian motion of the resonant masses, which appears at the output after passing through the mechanical transfer function of the system; the wideband amplifier noise, which appears directly at the output, and the narrowband back-action noise, originating from the back-energy flow from the amplifier, which excites the resonant masses.

The useful bandwidth of such detectors is by no means limited to the very narrow width of the high Q mechanical resonance. Rather, it is the amplifier noise that limits the bandwidth. The lowest spectral noise is found in the frequency region where the narrowband (thermal plus back action) noises dominate the amplifier noise, and there the noise level is the sum of the two. As a consequence, any reduction in the amplifier noise and/or increase in transducer coupling increases the antenna bandwidth.

During these years, experimentalists devoted a continuous effort to improve the read-out systems to reach the quantum limit in the displacement sensitivity. Different technologies are now under study. We summarize them below.

- Capacitive and inductive read-out. The operative bar detectors use SQUID-based read-outs, capacitive or inductive. One of the crucial improvements with respect to the state-of-the-art technology regards the energy resolution of the SQUID amplifier. Up to now the best performance achieved on a bar detector is obtained with a double SQUID amplifier and corresponds to about $700\hbar$ [11], but an energy resolution of about a few quanta in SQUID amplifiers without input load has been obtained [12] and of about $25\hbar$ in a SQUID coupled with a high Q input resonant load [13]. Specific R&D is ongoing in Italy (INFN and CNR—Istituto di Fotonica e Nanotecnologie), in the AURIGA and ROG collaborations, and The Netherlands (Leiden University in collaboration with Twente University) in the MiniGRAIL collaboration. R&D is also ongoing on capacitive and inductive transducers. We describe in the following section the results obtained so far, both on transducers and double-SQUID amplifiers.
- Optical read-out. The AURIGA group developed an optical-based resonant read-out [14], tested on a room temperature bar showing performances comparable to capacitive read-outs [15]. This system will soon be cooled to liquid helium temperatures [16].
- Parametric read-out. Re-entrant cavities as electromechanical transducers are currently being developed for Mario Schenberg, and will be pumped by ultra-low phase noise feedback oscillator [17, 18]. The parametric read-out is also being developed by the ROG collaboration [19].

3. Bar detectors

Bar detectors are now in the continuous observational mode with a very high duty cycle. For all four detectors in operation (ALLEGRO, AURIGA, EXPLORER and NAUTILUS [20–22]), it is near 100%, only limited by cryogenic operations. The behaviour shows a good stationarity, also during working hours. The noises of the detectors are well modelled and understood. During the last few years, thanks to the upgrades of the read-out systems, the bar antennas have gained a significant increase in the detection bandwidth, which is now of the order of tens of hertz at the level of 10^{-20} Hz$^{-1/2}$.

3.1. ALLEGRO

ALLEGRO was the first antenna to reach a very stationary behaviour, with high duty cycle and small excess, non-Gaussian, noise. A unique feature of the detector is the capability to rotate on air bearings, recovering optimum performance in a very short time. The current run started in May 2004. A refurbished inductive resonant transducer from the Maryland Group followed by a Quantum Design dc SQUID was installed. The detector operated mostly in IGEC2 orientation, parallel to European bars, except during S4 when it was rotated to optimize data taking in coincidence with LIGO. Calibration of the detector is currently being refined to determine the overall scale factor relating data to the gravitational strain. Using the most pessimistic estimate of the scale factor, the sensitivity is $\tilde{h} \simeq 4 \times 10^{-21}$ Hz$^{-1/2}$ with a bandwidth at the level of 10^{-20} Hz$^{-1/2}$ of about 20 Hz [23].

The introduction of a resonant transducer greatly improves the coupling between the bar and the amplifier, but the bandwidth is intrinsically limited, because of the higher thermal noise injected in the system by the lighter resonant mass. The use of multimode resonant transducers should permit further improvements of the detector bandwidth. A few two-mode transducer prototypes have been realized [24, 25] or are under development [6, 7] to obtain three-mode operation of the resonant-mass detectors.

A new two-mode inductive transducer, designed at Maryland University, is being built by the ALLEGRO group [23]. It will be installed in the next upgrade together with a double SQUID amplifier, based on the AURIGA design, to provide a significant increase in sensitivity. The goal is a sensitivity of $\tilde{h} \simeq 10^{-21}$ Hz$^{-1/2}$ over a bandwidth of 80 Hz.

3.2. AURIGA

The AURIGA group has developed an alternative two-mode transduction system in which the resonant amplification is realized by means of a resonant mechanical mode plus a resonant electrical matching network [3]. AURIGA is at present equipped with a capacitive resonant transducer, matched to a double stage SQUID amplifier by means of a tuned high Q electrical resonator. The resulting three-mode detection scheme widens significantly the bandwidth of the detector. The spectral sensitivity obtained with the detector operated at 4.5 K is better than 10^{-20} Hz$^{-1/2}$ over 110 Hz, and in good agreement with the expectations.

Thanks to the upgrade of the suspension system, done in May 2005, also the duty cycle of the AURIGA detector is very high, limited by cryogenic maintenance operations. AURIGA is now suspended on four commercial seismic isolation stages, consisting of pendula in the horizontal directions and air damper along the vertical. For all three degrees of freedom, the cut-off frequency is about 1 Hz. The detector output spectrum is clean of spurious lines, both during working days and weekends [26].

R&D on capacitive transducers is in progress, aiming at the increase of the maximum bias voltage applied to the transducer electrodes by about a factor of 10. At present electrical fields in the range of 10 MV m^{-1} are achievable. The goal of this R&D is to reach electrical bias fields of the order of 100 MV m^{-1}, by studying the surface finishing effect, the electrodes conditioning procedure and the effect of dielectric films.

The present run will be stopped in 2007 to install the dilution refrigerator and cool the bar down to 100 mK. The expected sensitivity of AURIGA operating at ultra-low temperature is $\tilde{h} \simeq 3 \times 10^{-22}$ Hz$^{-1/2}$ with a bandwidth of 90 Hz at the level of 10^{-21} Hz$^{-1/2}$.

3.3. EXPLORER and NAUTILUS

Both EXPLORER and NAUTILUS are equipped with a rosette geometry capacitive transducer [27], with a gap of the order of 10 μm, and a commercial Quantum Design single-stage dc SQUID, with energy resolution of a few thousand $\hbar$. These read-outs were installed in 1999 and 2002 on EXPLORER and NAUTILUS, respectively, achieving a considerable increase of the useful signal bandwidth [28] and, thus, an increase of sensitivity.

At present EXPLORER is cooled to 2.6 K and NAUTILUS to 3.5 K, both reach peak sensitivities of about 1–2 $\times 10^{-21}$ Hz$^{-1/2}$ and a bandwidth, at the level of 10^{-20} Hz$^{-1/2}$, of about 40 Hz. The noise temperature of the detectors is below 2 mK, corresponding to a sensitivity to GW ms bursts $h = 3 \times 10^{-19}$ [29].

The NAUTILUS detector will be cooled down to 100 mK by the end of 2005. Since all the noise components scale down with the thermodynamic temperature, a better sensitivity is expected.

In the next few months, a further upgrade is planned, with a new capacitive read-out, based on a double-gap transducer and a double SQUID amplifier.

The transducer coupling or efficiency β is given by the ratio of the mechanical energy of the transducer and the electromagnetic energy stored in the gap, and for a capacitive transducer it becomes $\beta = \frac{CE^2}{m\omega_0^2}$, where C is the total capacitance of the transducer, E is the biasing field, m is the equivalent transducer resonant mass and ω_0 is its resonance frequency. It turns out that a way to increase β is to increase the capacitance C. The idea followed by the ROG Collaboration is the double-gap transducer. The resonant mass is enclosed between two identically spaced electrodes, i.e. two identical gaps. This setup has the net effect to double the total capacitance C of the transducer, thus to increase the transduction efficiency β. Moreover, by properly biasing the two gaps, one with a positive voltage and the other with a negative voltage with respect to the resonator, it is straightforward to see that the signal current flowing in the primary coil of the transformer is twice that in the case of a single gap transducer.

A double-gap transducer has already been designed, assembled and tested at liquid helium temperatures [30]. The value for both gaps was of the order of 15 μm and the mechanical quality factor was found to be 1.0×10^6 when the transducer was biased with a field of about 20 MV m^{-1}.

The ROG collaboration has developed a double SQUID amplifier, with the sensor SQUID designed and built at the CNR-IFN of Rome [12]. The device, coupled to a high Q input resonant load, has been tested down to 2 K. An energy resolution of 70$\hbar$ has been measured [31]. Up to now, it is the best energy resolution measured at this temperature. The system is very promising. It will soon be tested at ultra-low temperatures and installed in the detectors. The expected sensitivity for NAUTILUS equipped with the new read-out is $\tilde{h} \simeq 3 \times 10^{-22}$ Hz$^{-1/2}$ with a bandwidth of 40 Hz at the level of 10^{-21} Hz$^{-1/2}$.

4. Spherical detectors

In a cylindrical bar, only the first longitudinal mode of vibration interacts strongly with the GW (the cross section of the higher frequency longitudinal odd modes decreases as $1/n^2$, where n is the order of the mode). Consequently only one wave parameter can be measured: the amplitude of a combination of the two polarization states.

On the other hand, each quadrupole mode of a spherical mass is five-fold degenerate (its angular dependence can be described in terms of the five spherical harmonics $Y_{lm}(\theta, \varphi)$ with $l = 2$ and $m = -2 \cdots + 2$) and presents an isotropic cross section. Because the metric deviation tensor h_{ij} is traceless, its angular expansion can be done completely with the five ordinary spherical harmonics of order 2, so that a spherical detector can determine the GW amplitudes of the two polarization states and the two angles of the source direction.

The method first outlined by Forward [32] and specified by Wagoner and Paik [33] consists of measuring the sphere vibrations in at least five independent locations on the sphere surface so as to determine the vibration amplitude of each of the five degenerate modes. The Fourier components of the GW amplitudes at the lowest order quadrupole frequency and the two angles defining the source direction can be obtained as proper combinations of these five outputs [34–37]. The signal deconvolution is based on the assumption that in the laboratory frame all five quadrupolar spheroidal modes are usually excited by the GW, whereas in the wave reference frame (the frame in which the z axis is aligned along the wave propagation direction) only the modes with $l = 2$ and $m = +2$ and -2 are excited by the GW, as the helicity of a GW is 2 in general relativity. One can take advantage of this to deconvolve the Euler angles between the laboratory frame and the wave frame, thus finding the GW amplitudes in the wave frame and the wave propagation direction. There will remain a 180° ambiguity for a single sphere; however, this ambiguity can be removed by measuring the time delay between two largely separated detectors operated in coincidence.

Many different configurations have been discussed [34–37] where explicit formulae can be found. In particular, Johnson and Merkowitz proposed the truncated icosahedron configuration of motion sensors (TIGA) that solved the major practical problems in deconvolving a GW signal [34].

It is also remarkable that the cross section of a spherical detector at the second-order quadrupolar mode is only a factor of 2.6 lower than that at the fundamental mode. This means that this detector can be used to advantage at two frequencies, thus giving two independent measurements of the GW parameters.

5. The SFERA detector

In the last few years, significant advancements have been made to realize a spherical antenna. The barriers already overcome are

- Practicality of the truncated icosahedral symmetry for the positioning of the transducers was demonstrated and the coupling of six resonant transducers with the five quadrupole modes of a spherical mass is well understood [38].
- Cooling large masses to ultra-low temperatures for long periods of time is possible and was demonstrated by the operation of the 2.5 ton NAUTILUS antenna at 100 mK since December 1995 [39], of the AURIGA detector at 200 mK [40] and by the initial operation of MiniGRAIL [41].
- The five quadrupole modes of a real spherical mass are independent and have the required high mechanical Q at ultra-low temperatures [42].

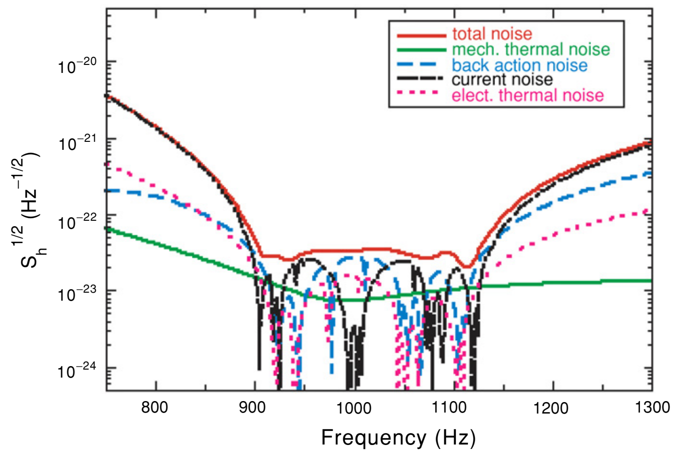

Figure 1. Expected strain sensitivity of a 2 m diameter CuAl spherical detector, cooled at 30 mK, equipped with a quantum limited read-out. The expected sensitivity with a $20\hbar$ read-out is about $S_h^{1/2}(f) = 3 \times 10^{-22}$ Hz$^{-1/2}$ over 200 Hz.

- The possibility of obtaining large pieces of material suitable for a spherical detector has been investigated. Large pieces of CuAl alloys, with high quality factors [43, 44], can be built.
- The results obtained with the MiniGRAIL detector allowed us to test techniques useful for a large spherical antenna. MiniGRAIL is large enough to develop techniques applicable to a large antenna, but is of a sufficiently manageable size to allow for rapid measurements and design changes. MiniGRAIL has been important to address the following issues.
  - Design and construct a complete cryogenic system, mechanically decoupled from the suspension system and the detector, for a sphere of about 1 m diameter, based as much as possible on state-of-the-art, commercially available items.
  - Demonstrate the operation of the cryogenic system at a very low acoustic noise level, and show that it is capable of rapidly cooling a 1 m diameter sphere to low temperatures.
  - Design and construct a suspension system with at least −350 dB of attenuation, without appreciable upconversion mechanisms.
  - Investigate the problems of data acquisition and processing by observing the five quadrupole modes of a sphere.
  - Investigate methods of attaching a resonant transducer to a sphere while maintaining a high mechanical Q.
  - Prove the quality of the solutions adopted by measuring the Brownian motion of one of the quadrupole modes of the sphere, at 4 K, with a state-of-the-art resonant transducer and SQUID amplifier.

A resonant-mass spherical detector with radius $R = 1$ m, made of a CuAl6% alloy, has been proposed. The mass of such a sphere will be 33 ton. The first quadrupolar spheroidal mode (i.e. the spheroidal mode $l = 2, n = 1$), which is at a frequency of about 1 kHz, will be monitored using six transducers in the TIGA configuration. At an advanced stage, also the first harmonics (i.e. the spheroidal mode $l = 2, n = 2$), which is at a frequency of about 2 kHz will be monitored. The expected sensitivity for a 2 m sphere is shown in figure 1.

In conclusion, a spherical resonant-mass detector with the specification proposed, will reach, in a first stage of operation, a sensitivity about equal to that of a large-scale interferometer such as VIRGO or LIGO, in their initial configuration, over the frequency range 900 Hz $< f <$ 1100 Hz. In the final configuration, it will reach over the same frequency window a sensitivity $S_h^{1/2}(f) = 3 \times 10^{-23}\,\mathrm{Hz}^{-1/2}$, approximately equal to the projected sensitivity of advanced interferometers.

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