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SFERA: the new spherical gravitational wave detector

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Abstract. This paper describes the main properties of gravitational wave detectors of spherical shape, the experimental achievements obtained up to now towards the development of this kind of detectors and the expected sensitivity of SFERA, a 2 meters diameter spherical antenna proposed as the next step in the development of resonant gravitational wave detectors.

1. Introduction

Resonant bar detectors are in the continuous observational mode with a burst sensitivity $h = 2 \cdot 10^{19}$ or spectral amplitude of $h(f) = 10^{-21}\,\mathrm{Hz}^{-1/2}$ in a bandwidth of tens of Hertz, and a duty cycle near 100% [1]. Such a sensitivity should allow the detection of the strongest sources in our Galaxy and in the Local Group. Gravitational wave (GW) detectors of spherical shape are considered as the natural evolution of resonant bar antennas, because of their unique capability to reconstruct the properties of the incoming GW. We will summarize in Section 2 the most relevant features of GW spherical detectors, and in Section 3 the state of the art of the proposed 2 meters diameter spherical detector, SFERA, which is expected to have a sensitivity competitive with the large interferometers in a 200 Hz bandwidth around 1 kHz.

2. Properties of resonant spherical detectors

Ideally, GW observatories should be able to determine both the source direction and the wave forms of GW signals. Resonant bar and interferometric detectors essentially detect the GW signal polarization component along their maximal sensitivity axis. They have an optimal sensitivity along some direction, and reduced sensitivity along the other directions (as well as blind directions). In terms of metric components they can provide an estimate for only one component of the gravitational wave strain tensor h_{ij}. On the other hand, a spherical detector is very promising because it has five degenerate quadrupole modes of vibration, all interacting with the GW. A spherical antenna is then a truly omnidirectional detector, equally sensitive to GWs of all polarizations (h_+ and h_x) and directions and gives the unique opportunity to measure the wave direction. The complete GW field tensor could be reconstructed, allowing to test whether General Relativity correctly predicts their tensor character [2]. The presence of the five output channels also gives a veto that distinguishes a true GW signal from a spurious excitation due to noise, checking the transverse nature of the disturbances. This is of great importance, since all GW detectors, both resonant masses and interferometers, are affected by non-gaussian disturbances that simulate GW signals.

If we include in our analysis the presence of noise, then the ability to reconstruct the arrival direction will depend on the signal-to-noise ratio. If we denote by SNR the signal-to-noise ratio in energy, it can be shown that the error made on the determination of the arrival direction is $\Delta\Omega = 2/SNR$, where $\Delta\Omega \equiv [(\Delta\theta)^2 + \sin^2\theta(\Delta\phi)^2]$ and θ and ϕ are the angles defining the incoming GW direction. It can be shown that this resolution, which is obtained from a single spherical resonant-mass detector, is better than what can be achieved, with the same SNR, combining the outputs of three interferometers [3, 4].

From this we see that interferometers and resonant spheres are really complementary: interferometers, due to their larger bandwidth, are much better at reconstructing the waveform, while a sphere is much better at reconstructing the arrival direction. Together, an interferometer and a sphere would be much more effective for opening up the field of GW astronomy. Moreover, the separate information that the sphere gives on h_+ and $h_?$ can be very important to reconstruct the parameters of the source.

The measurement of the oscillations of the 5 quadrupole modes of the spherical detector can be performed by sampling the position of a number of points on the sphere surface. For a sphere, monitoring the five quadrupole modes therefore requires at least five resonant transducers. However, a configuration of transducers which is expecially simple for deconvolving the output, the so-called Truncated Icosahedral arrangement (TIGA), requires a sixth transducer. In a sphere equipped with 6 resonant transducers, the motion induced by a GW can be fully decomposed as the sum of quadrupole modes [5].

Another relevant feature is that a sphere is also sensitive at the resonant frequency of its second order quadrupolar modes [6]. Considering that, in the TIGA configuration, the six transducers are all placed on the same hemisphere, it is in principle possible to put six resonant transducer in the TIGA configuration on one hemisphere, to monitor the fundamental quadrupolar mode (at a frequency of about 1 kHz for a CuAl sphere with a diameter of 2 meters) and six more on the other hemisphere to monitor its first harmonics (at a frequency of about 2 kHz for the same sphere). Many typical astrophysical bursts are expected to have Fourier components extending over the 1-2 kHz range. For such a signal, a sphere with two TIGA systems of transducers would be an extraordinarily clean detector. The first system of transducer provides, as discussed above, a veto (checking the transversality of the excitation) and a determination of the direction of arrival of the signal. The second system of transducers would provide another veto (checking again the transversality of the excitation) as well as a second independent determination of the direction, and the latter determination of the direction must be consistent with the former. Such a system would therefore provide a remarkable background rejection rate. This is of great importance, given that all GW detectors have false alarms. Furthermore, when observing a chirp GW signal, the measurement of the time delay between excitations of the first and second quadrupole modes on a spherical detector will determine the frequency acceleration of the chirp signal and allow the chirp mass to be estimated [7].

3. The SFERA detector

We propose to build a resonant-mass spherical detector with radius R = 1 meter, made of a CuAl6% alloy. The mass of such a sphere will be 33 ton. We will monitor its first quadrupolar spheroidal mode which is at a frequency of about 1 kHz, using six transducers in the TIGA configuration. At an advanced stage, we will also monitor its first harmonics, which is at a frequency of about 2 kHz. The choice R = 1 meter, which for our choosen material gives a resonance frequency of 1 kHz, is the best compromise, which allows us to explore a region of frequency considered among the most interesting for GW astrophysics, while keeping under control the financial cost and the experimental complexity.

In the last few years significant advancements have been made towards the complete design of a GW observatory based on massive resonant spherical detectors. The achievements regard the

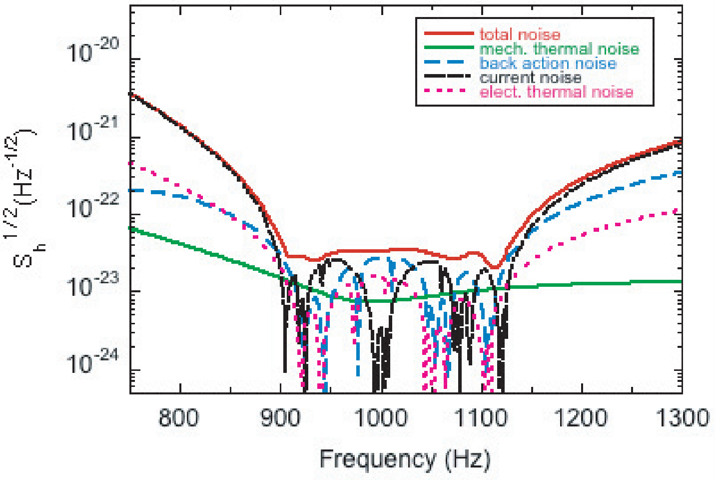

Figure 1. Expected strain sensitivity of a 2 meters diameter CuAl spherical detector, cooled at 30 mK, equipped with a quantum limited read out. The contributions of the different noise sources are shown. The sensitivity of the sphere does not depend on the polarization and direction of the incoming GW.

practicality of the truncated icosahedral symmetry for the positioning of the transducers, the study of the coupling of the 6 resonant transducers with the 5 quadrupole modes of a spherical mass, the possibility of obtaining large pieces of material suitable for a spherical detector, such as CuAl alloys, the measurement of the mechanical quality factor of this material at ultra-low temperatures.

The operation of the 2.5 ton NAUTILUS antenna at 100 mK since December 1995 [8], and of the AURIGA detector at 200 mK [9] demonstrated the possibility of cooling large masses to ultra-low temperatures for long periods of time.

The results obtained with the MiniGRAIL detector [1], the 0.6 meters diameter spherical antenna developed at the Leiden University, allowed 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. It has been important to address issues such as the design and construction of a complete cryogenic system, mechanically decoupled from the suspension system and the detector, the operation of the cryogenic system at a very low acoustic noise level, the possibility of rapidly cooling a 1 meters diameter sphere to low temperatures, the design and construction of a suspension system with at least -350 dB of attenuation, without appreciable upconversion mechanisms, the investigation of the problems of data acquisition and processing by observing the 5 quadrupole modes of a sphere.

At present, R&Ds are in progress in the bar detectors community to develop quantum limited read out systems, with both passive and parametric transducers [1]. The proposed strategy for the SFERA project is to continue these developments and to use the best device available at the moment.

The study of the cosmic rays as a source of background for the SFERA detector is in progress. Its aim is to understand if at the final sensitivity an underground location is necessary to reduce the rate of false alarm events, or if an opportune shielding combined with a cosmic ray veto system can be effectively implemented. In any case, the plan is to install the detector for assembling and commissioning at surface, and eventually to move it underground if needed.

The expected sensitivity for a 2 meters sphere is shown in Fig. 1. The curve represents the sensitivity that can be achieved with a quantum limited read-out. The curve shows that a spherical resonant-mass detector with the specifications proposed, will reach a sensitivity equal to or even better than that of a large scale interferometer such as VIRGO or LIGO, over the frequency range 900-1100 Hz.

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