

The Mario Schenberg Gravitational Wave Antenna

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Abstract This article is an account of the work done in the Mario Schenberg gravitational wave antenna up to date, focusing mainly in the participation of the Laboratório de Estado Sólido e Baixas Temperaturas (LESBT) do Instituto de Física da Universidade de S. Paulo. The text starts with an introduction describing the problem, the Brazilian project, and the participant institutions. This is followed by a description of the construction of the infrastructure, initial tests, and final basic assembly at the LESBT. Results are presented for the thermal and mechanical behaviors of the cryogenic system and for the development of active transducers in its various stages, culminating with the last version in which the project sensitivity of $\sim 4 \times 10^{-20} \text{ Hz}^{-1/2}$ was attained.

Keywords Gravitational waves · Mario Schenberg antenna

1 Introduction

The recent announcement of direct detection of gravitational waves (GW) by the Laser Interferometer Gravitational-Wave Observatory, LIGO [1], put an end to a long quest and opened up a new window for cosmological and astronomical studies!

GWs were predicted by Einstein's 1916 theory of gravitation and consist of space-time distortions generated by mass accelerations propagating with the speed of light [2]. Its interaction with matter is so weak, however, that direct detection defied experimentalists until now, and it was only possible through a fantastic technological feat. The total amplitude of the linear relative space deformation, measured by the LIGO interferometers, was a mere $h = (\delta l/l) = 10^{-21}$!

Indirect evidence for the existence of such minuscule deformations had been strongly established by R. A. Hulse and J. H. Taylor [3] decades ago. They measured the variation of the period of a binary pulsar system and showed that the energy loss corresponded precisely to that of the emission of GWs as predicted by Einstein [4] (Fig. 1). For this work, they were awarded the Nobel Prize of 1993.

The first attempt of direct detection came from the work of Joseph Weber in the 1960s [5]. His idea was to measure the deformations of a cylindrical bar (1.5 m long and 1 m diameter), resonantly excited by the passage of a GW. Such deformations were transduced into electrical signals by strain gauges (piezoelectric sensors) distributed along the bar (Fig. 2). His initial claim to success [6] was strongly contested and eventually denied by careful repetition of his experiments [7]. He had achieved a relative linear deformation sensitivity h of order 10^{-16} which, although impressive for the instrumentation he had, was not nearly enough for GW detection. An estimate, from Einstein's theory, of the value of h necessary to detect an explosion of a supernova in the center of our galaxy, consuming (very optimistically) 1 % of the Sun's mass in the emission of gravitational waves in 3 ms, is $h \sim 10^{-18}$! The probability of a similar event is of order one per century! Clearly, much larger sensitivities than 10^{-16} were needed for a reasonable expectation of detection.

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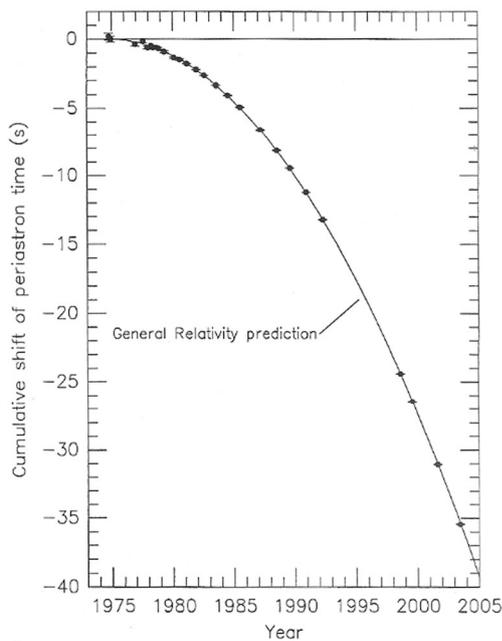


Fig. 1 The plot shows that the measured energy loss of the binary system agrees with Einstein's prediction through gravitational waves (from ref. [3])

The advent of the Josephson effect [8] opened up the possibility for large improvements in signal amplification (and consequent sensitivity), and more bar detectors, similar to Weber's, were built [9]. Another improvement was to cool the bar to low temperatures to reduce thermal noise (Fig. 3) [10]. Simultaneously, interferometry was considered as another method of detection [11], and eventually large interferometers began to be built in the USA and Europe [12–14]. These however would bear development and construction costs orders of magnitude larger than those of resonant masses.

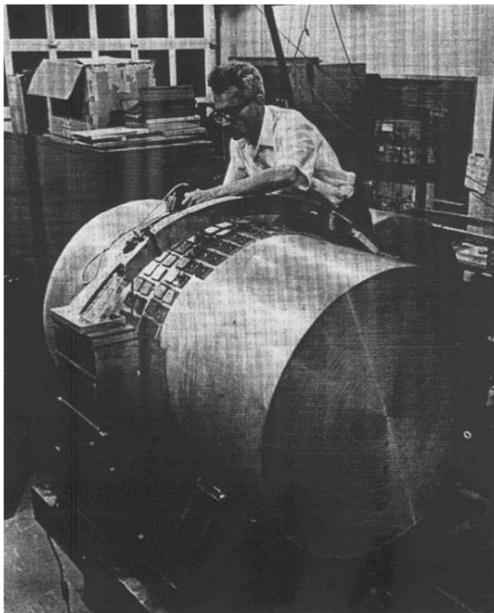


Fig. 2 Weber and his aluminum bar



Fig. 3 A view of the open cryostat for the bar detector named “Allegro” at Louisiana State University. Also seen is one of the authors, ODA, then working for his PhD (photo of 1990)

For most of the cosmic events that could generate large GWs, the predicted frequencies were in the low end of the spectrum. Weber's bar resonated at 1.66 kHz. Most of the detectors that followed were tuned to around 0.7 kHz, a reasonable compromise between size (the lower the frequency, the larger the bar) and expected GW frequencies. The interferometers, on the other hand, could be designed to be sensitive in a much broader frequency range, but always in the vicinity of 0.7 kHz.

The most advanced project today is LIGO, a complex of two very large interferometers built in the USA [15], 3000 km from each other. It is, presently, in its last phase of improvements with a relative space deformation sensitivity of $h \sim 10^{-23} \text{ Hz}^{-1/2}$. This almost incredible sensitivity should allow for the detection of events not only in our own galaxy but also in the neighboring ones, thus increasing significantly the number of events and consequently the possibility of detection. The signal reported by LIGO was generated by the coalescence of two black holes of 29 and 36 solar masses, forming a single 62 solar mass black hole [1], distant 1.3×10^9 light-years from us.

The overall cost of the LIGO project is over one billion dollars, and this is the only one of the several projects going on around the world. Such level of investments reflects the importance that is given to the expected scientific knowledge to be obtained and also to the resulting technological developments. The extreme complexity of these instruments places them in the frontier of technological advancements.

2 The Brazilian Project

The first Brazilian project for the study and detection of GWs was devised in the 1990s, by a group at INPE (Instituto Nacional de Pesquisas Espaciais) led by Odylio D. Aguiar. It was named “Projeto Graviton” [16]. It contemplated a resonant mass type but with major differences from the already existing antennae. First, instead of a bar, the resonant mass should be a sphere. Besides, the transducer should be active, and not passive as in the existent bars.

Spherical masses are more sensitive to GWs than bars, because there is more mass (about 16 times more) involved in the quadruple mode oscillations for the same resonant frequency. Another point was the fact that, in a sphere, transducers can be set up in all directions, and when strategically placed, all components of the wave tensor can be determined [17]. This allows, for instance, for establishing the direction of the wave and consequent direct association with source, something not possible with bars or interferometers individually.

Active transducers, in which a microwave cavity is modulated by the vibrations of the sphere, had also been studied and demonstrated [18]. Again, for these transducers, the possibility of improved sensitivity had been pointed out by many groups [19, 20].

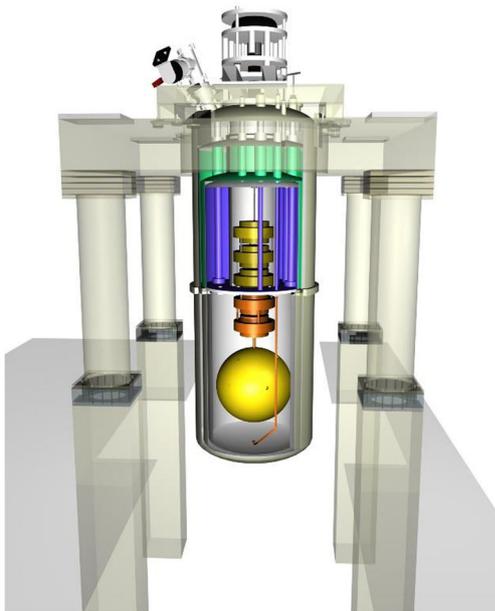


Fig. 4 Schematic drawing of the dewar assembly in S. Paulo. The suspension of the sphere has an air cushion on top and a series of five sets of mass-springs for mechanical insulation. Cooling is achieved by anchoring the suspension to liquid nitrogen (*green*) and liquid helium (*purple*). The dilution refrigerator (not shown) cools the fourth mass (*second from the bottom*), which cools the sphere through a copper rod. All thermal contacts were made through parts designed to minimize transmission of mechanical vibrations



Fig. 5 *On the top*, the pit with the columns for the hydraulic arms. *At the bottom*, the platform being assembled on top of the columns

The intended higher sensitivity of the Brazilian project would demand cooling to very low temperatures for further minimization of thermal noise and the incorporation of a dilution refrigerator was planned. Cooling the resonating mass to very low temperatures, however, posed several new problems. First, the sphere had to be made of a good thermal conductor. The existent bars were of an aluminum alloy (A15056) known to have extremely good mechanical quality. This meant that any resonating vibration would decay very slowly (very low loss per cycle), a characteristic important for the extraction of a signal buried in the noise. Unfortunately, at very low temperatures,



Fig. 6 In front of the milling machine at Italbronzes S.A. *From the left*: Italbronzes’s Director Jaime Ortiz, O. Aguiar, G. Frossati, N. Oliveira Jr., and Sergio Turano (student)

aluminum becomes superconductor with low thermal conduction. The solution would be to find a copper alloy with good enough mechanical quality, and this was one of the first tasks in the project. The second major problem was the contact between the refrigerator and the sphere. The necessary thermal contact would have to be done with minimum mechanical contact since the refrigerator produced vibrations that should not reach the sphere. The proposed solution was to cool part of the mechanical isolation filters together with the sphere, so that the contact of the cold source would not be made directly to the sphere and the added vibrations would be filtered.

The proposed mechanical isolation system consisted of hanging the sphere from several interconnected sets of masses and springs tuned to eliminate high frequencies (mechanical low-pass filters). Also, an air cushion was provided on top of the suspension rod to minimize low frequencies.

Another problem was size since a copper sphere tuned to 0.7 kHz would have about 3 m in diameter and weigh more than 100 t. Downsizing would imply higher frequencies with somewhat less chance of predicted events to be detected.

3 LESBT

For assistance with the low-T problems and cryogenic setup, Aguiar went to the Low Temperature Lab at the IFUSP (LESBT). In those days, a frequent visitor of LESBT was Prof. Giorgio Frossati, then the Director of the Kammerling Onnes Laboratory at the University of Leiden in Holland and a leading scientist in Low Temperature Physics. He became very interested in the project and began to collaborate with Aguiar. Soon, two proposals were presented, one in Holland and one in Brazil, both for a 3-m sphere. Unfortunately, both ran into funding problems.

The next step was, then, to devise a project that could, at least initially, minimize costs. The main idea was to build a



Fig. 7 Finished sphere. Precision holes drilled in strategic places to hold transducers are shown



Fig. 8 Sphere suspended with mass-spring filters. The top three masses were of CuAl (6 %). The two bottom ones were of copper. They should be cooled by the dilution refrigerator and then should cool the sphere through a copper rod attached to the center of the sphere (not seen)

device that would fit and could be managed in the existent infrastructure of both low-T labs, in S. Paulo and in Holland. The sphere was downsized to a diameter of 65 cm, tuned to a frequency of ~ 3.2 kHz. A survey of the literature indicated that several important prospective sources should produce waves in the vicinity of that frequency. A proposal was then presented to FAPESP and, after some discussion, was approved. Simultaneously, a similar project was presented in Holland. The two projects ran in parallel, and the only important difference was that, while the Brazilian effort would develop active transducers, in Leiden, passive transducers similar to those in the already existent bars, were to be used. The Dutch antenna was named MiniGRAIL, because the original



Fig. 9 Installation of the 1K-pot for the dilution refrigerator



Fig. 10 View of the open cryostat before cool down

project (3-m sphere), had been named GRAIL. The Brazilian one was named Mario Schenberg, a homage to the well known USP professor [21].

Detailed drawings of the whole system were prepared and two identical cryostats were custom built in the USA [21]. To support the Dewar and allow for all its assembling and disassembling operations, a ditch had to be excavated in the

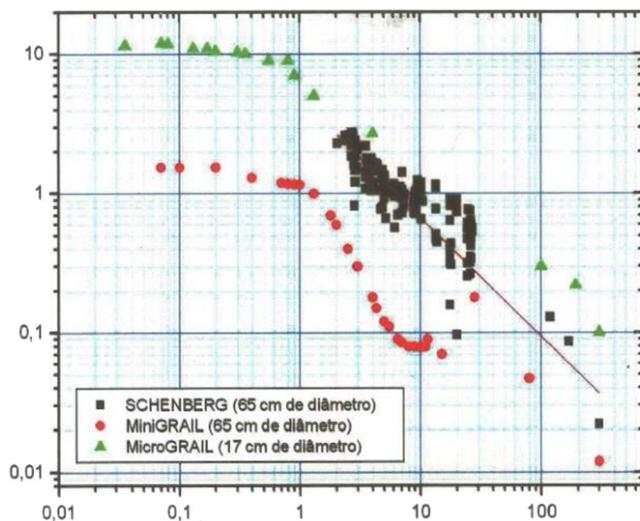


Fig. 11 Measured mechanical quality factor Q_M (in millions) vs. temperature (Kelvin) [24]. For the S. Paulo sphere (black squares), a good agreement is found with the measurements for the 16 cm sphere (green triangles). For the MiniGRAIL sphere (red dots), however, a spurious dissipation occurs below 10 K. Eventually, a second sphere was casted for Holland.

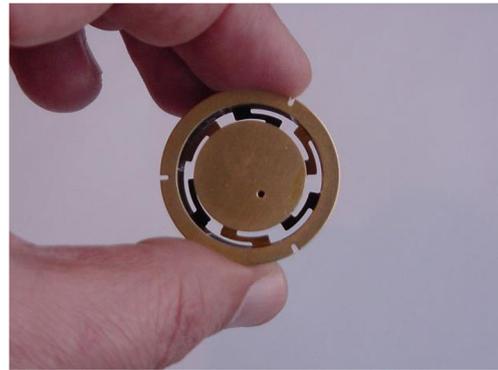


Fig. 12 View of the first transducer. The outer ring is for fixation at the sphere and is attached by springs to a centerpiece that incorporates the vibrator that closes the microwave cavity

floor of the S. Paulo lab, and a concrete platform, moved by a hydraulic system inside concrete pillars, was built (Figs. 4 and 5). On top of the room, a two-way mobile crane was designed and constructed. Besides, a mezzanine floor was mounted sideways to accommodate electronics, computers, and data acquisition. At the end, it was, altogether, a very compact system. In Holland, a similar system was set up.

4 The Sphere

The most important initial project was to determine a copper alloy for the sphere. The test consisted of exciting a small spherical sample (16 cm diameter) of a particular alloy and measuring



Fig. 13 Experimental apparatus used to measure the superconductive klystron cavity's resonant frequency and loaded electric Q factor in reflection mode: (i) overall view of the setup composed of a standard liquid helium dewar, testing cryostat, and Agilent 8722/ES vector network analyzer; (ii) the bottom part of the testing cryostat, where the microwave cavity is located inside; (iii) the top part of the testing cryostat, which is connected to the vector network analyzer. An electric Q factor as high as ~ 300 k was recorded [26]

the decay of the oscillations produced, as a function of temperature. The excitation was done by hitting the sphere with an electrically driven hammer. One was looking for the highest mechanical quality factor defined as $Q_M = f_0 \tau$ (where f_0 is the frequency and τ is the time constant for the exponential decay) at very low temperatures (below 0.1 K). For this, a special cryostat had to be designed and built, and a large number of alloys were tested. The final choice was $\text{Cu}_{0.94}\text{Al}_{0.06}$ [22]. Most of this work was done at Leiden.

Next, a suitable foundry was selected to cast the spheres. Eventually, three spheres and the masses for the mechanical filters were precision casted and machined in a company in S. Paulo (Figs. 6, 7 and 8). Two of the spheres went to Holland.

5 The Mechanical Filters

As seen in Fig. 4, the sphere is suspended from five sets of mass-springs which, in turn, are suspended from an air cushion, all to filter mechanical vibrations. The shape of the masses, and especially of the springs, were subject of study, mostly through modeling. The initial springs, shaped like *C-clamps* were later substituted by simpler rods with even better

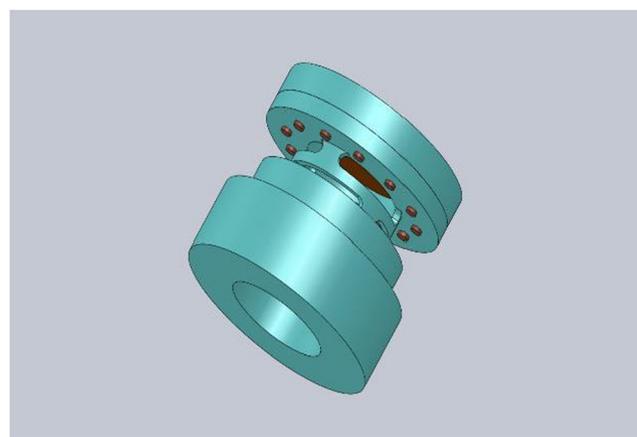
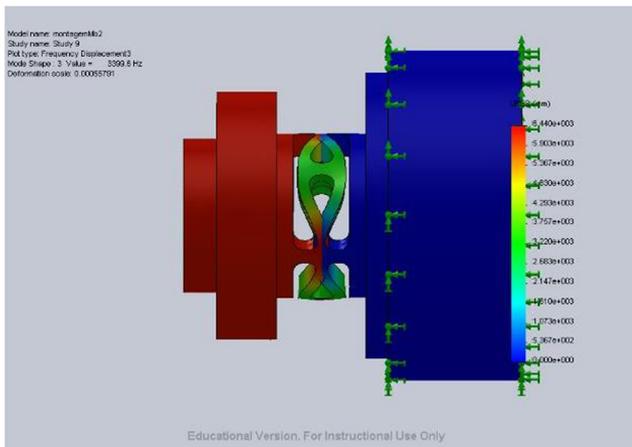


Fig. 14 Drawings of the fifth transducer



Fig. 15 The fifth generation of transducers: The two leftmost ones coupled to the 6.5 kHz monopole resonant frequency of the spherical antenna. The six others coupled to the 3.2 kHz spherical antenna's quadrupole resonant frequency. All set is made of very pure niobium (less than 100 ppm of impurities)

results. Overall, an attenuation of about 300 dB [23], around the resonating frequency, was obtained.

6 The Dilution Refrigerator

The high-power dilution refrigerator necessary to cool the sphere was designed by Frossati and the parts internal to the cryostat were built in Leiden in duplicate. Figure 9 shows the 1K-pot for the dilution refrigerator already installed in S. Paulo. The gas circulation and storage systems, together with respective controls, were designed and built in each laboratory



Fig. 16 Setup of the transducers on the sphere

separately. In S. Paulo, the container for the $^3\text{He}/^4\text{He}$ mixture had to be accommodated underground to save space.

7 First Cool Down

The first cool down of the sphere to helium temperatures took 110 h, 1.360 L of liquid helium, and 500 L of nitrogen. It was monitored by a number of thermometers set up throughout the system. From the study of the heat flow, plans for some improvements could be made reducing the amount of cryogenics to be used. Also, the mechanical quality factor Q_M of the sphere could be checked as a function of temperature (Figs. 10 and 11).

8 Transducers

Building a device capable of transforming extremely small mechanical vibrations into measurable electrical signals is among the most difficult and important tasks in a GW antenna, if not the most important. In the Schenberg antenna, it starts with a “mechanical amplifier,” that is, another mass-spring set, coupled to the sphere and tuned to the same frequency, but with a very small mass. Then, when the sphere is excited, the small mass will vibrate together, with the same energy and consequently with an amplitude amplified to the square root of the ratio of the masses. In the last version of transducer tested, the small mass is a membrane of 12.4 mg, which, coupled to the 287.5 kg effective mass of one spherical quadrupole mode, provides a mechanical amplification of $(287.5 \text{ kg}/12.4 \text{ mg})^{1/2} \sim 4800$. This membrane is, in turn, coupled to a microwave cavity and its vibration modulates the properties of the cavity [25].

The development of such a device was done by combining computer simulations with actual experiments until it was ready for testing at the sphere. After the full test, a careful analysis would indicate improvements and/or even new design directions. The main problems were to be able to precisely tune it to the vibration frequency of the sphere and to maximize the electrical quality factor Q_E . Five generations of transducers were built and tested [26].

Figure 12 is a picture of the very first design and Fig. 13 shows the test site. The last one built (the fifth generation, Figs. 14, 15 and 16) went to a full test just before this article was written. Although a full analysis was not completed yet, preliminary results show that sensitivity $\sim 4 \times 10^{-20} \text{ Hz}^{-1/2}$ was obtained.

9 Comments and Conclusions

After the basic cryogenic infrastructure was in place and working, the activity in the Schenberg antenna concentrated

in the development of the transducers. The objective is to reach the same order of magnitude in sensitivity as that of initial LIGO at 3.2 kHz. The last generation of transducers is already within one (or at most two) orders of magnitude from that. The fact is that each generation of transducers improved on the previous one. So, it is reasonable to expect that further work will achieve the objective.

The dilution refrigerator was not fully installed and tested, in part, because of the extreme difficulty of ^3He acquisition in the last decade. However, in Leiden, with a different schedule of priorities, the sphere was cooled to 65 mK [27, 28]. Since the two systems are identical it is reasonable to assume that the same solutions will apply in S. Paulo.

The detection reported by LIGO is certainly the first of many to come. Sensitivities will still be improved, including by the fact that the ultimate goal is to operate synchronously all the detectors being developed worldwide. The power of such observatory would be immense.

The Schenberg antenna is meant to be part of this worldwide observatory. The recent decision, within the Instituto de Física da Universidade de São Paulo, to transfer the project totally to INPE will in fact exclude the LESBT from that. It is clear, however, that this laboratory has successfully fulfilled its mission of providing infrastructure and expertise for as long as it was part of the Graviton Project. Reassembling the antenna at INPE will certainly take some time and cause a delay, but the exploration of gravitational waves as a tool to study cosmology, and astronomy in general, will be here for quite some time.

Naturally, only future observations, that will certainly come, can assert the possible contributions of spherical resonant detectors in studies involving GWs. Besides a narrow bandwidth, it will be hard for them to compete in sensitivity with interferometers. Important assets, however, are their omnidirectionality and, of course, their much lower cost.

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