Classical and Quantum Gravity

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To cite this article: O D Aguiar *et al* 2008 *Class. Quantum Grav.* **25** 114042

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Class. Quantum Grav. **25** (2008) 114042 (10pp) doi:10.1088/0264-9381/25/11/114042

The Schenberg spherical gravitational wave detector: the first commissioning runs

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Received 1 November 2007, in final form 31 March 2008
Published 15 May 2008
Online at stacks.iop.org/CQG/25/114042

Abstract

Here we present a status report of the first spherical antenna project equipped with a set of parametric transducers for gravitational detection. The Mario Schenberg, as it is called, started its commissioning phase at the Physics Institute of the University of São Paulo, in September 2006, under the full support of FAPESP. We have been testing the three preliminary parametric transducer systems in order to prepare the detector for the next cryogenic run, when it will be calibrated. We are also developing sapphire oscillators that will replace the current ones thereby providing better performance. We also plan to install eight transducers in the near future, six of which are of the two-mode type and arranged according to the truncated icosahedron configuration. The other two, which will be placed close to the sphere equator, will be mechanically non-resonant. In doing so, we want to verify that if the Schenberg antenna can become a wideband gravitational wave detector through the use of an ultra-high sensitivity non-resonant transducer constructed using the recent achievements of nanotechnology.

PACS numbers: 04.80.Nn, 95.55.Ym

1. Introduction

A single spherical antenna can instantaneously determine the wave polarization and localize its astrophysical source in the sky for any gravitational wave signal detected as long as one knows what the right gravitational theory is [1, 2], and, similarly, if one knows where the source is in the sky the right gravitational theory can be found. These advantages of a spherical antenna are due to its omnidirectionality achieved through the use of a sufficient number of transducers monitoring its fundamental mechanical modes [3, 4]. As a consequence, it is never 'blind' to any particular direction or polarization of the arriving wave [5]. It is equivalent to having many detectors operating together at the same time and site [6]. So, one can perform real-time data analysis with the signals of the transducers looking for correlations, which is impossible to carry out using detectors located at different sites.

There are only two existing spherical antennae in operation: one in Leiden (the Netherlands) and other in São Paulo (Brazil). Figure 1 shows a schematic view of the Brazilian Mario Schenberg detector [7]. The Schenberg CuAl6% antenna has a diameter of 65 cm and weighs 1.15 ton. It has nine little holes on its surface for up to nine transducers, six of which follow the truncated icosahedron configuration proposed by Johnson and Merkowitz [4], and one as a calibrator. At the standard quantum limit sensitivity it will have a strain noise power spectral density of $\sim 10^{-22}$ Hz$^{-1/2}$ [8]. It will operate in coincidence with the Dutch Mini-GRAIL antenna [9] and some long baseline laser interferometer detectors [10], searching for high-frequency events in the 3.0–3.4 kHz frequency bandwidth.

2. The commissioning runs

The Mario Schenberg gravitational wave detector started its commissioning phase at the Physics Institute of the University of São Paulo, in São Paulo city, in September 2006, under the full support of FAPESP. Three initial transducers were specially constructed for this phase. They were supposed to be robust (fail proof) rather than sensitive, in order to increase the chances of operating at some level of sensitivity during this first test. Therefore, the electrical quality factor (Q_e) was only $\sim 10^4$ at 5 K (because no niobium layer was deposited on the walls of the cavity and, so, the walls were not superconductive), the silicon membranes had not yet been installed, the df/dx was only 50 MHz μm^{-1}, and one of the transducers was not mechanically resonant to the antenna's resonant frequencies (see its detailed description in the figure caption). It measured the motion of the sphere surface directly, without any amplitude transformation. Figure 2 shows the schematic view of this 'non-resonant transducer' or inertial transducer (the other two used were one-mode transducers [7]) and the detailed view of the microstrip pairs of antennae can be seen in figure 3. These runs were performed during the third overall cryogenic run of the detector.

The first transducer tests were performed in July 2006, at room temperature, with no vacuum around the sphere, and were successful. The three initial transducers worked pretty much all the time, even when pumped with a microwave carrier far from the cavity electric resonance frequency. Of course the detuning of the pump oscillator from the transducer's

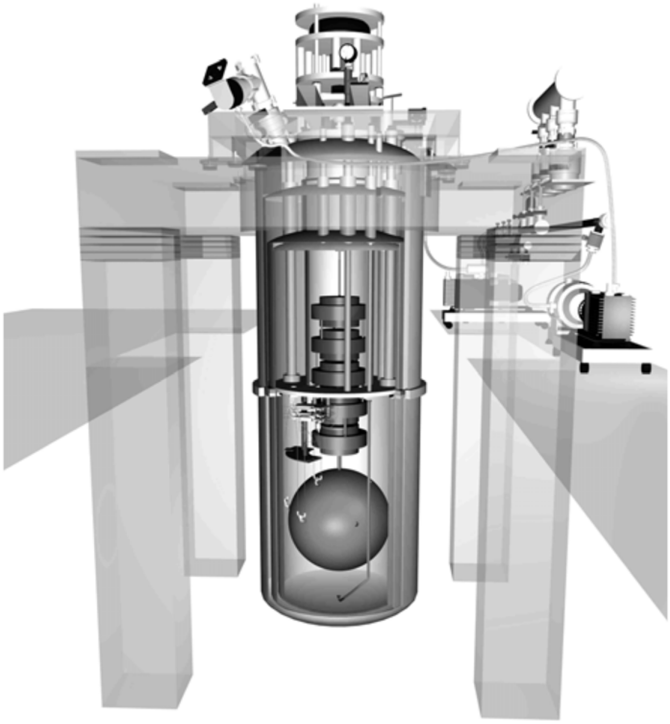


Figure 1. A schematic view of the cryogenic Mario Schenberg gravitational wave detector is seen. The vacuum pumps (mechanical and turbo) are shown on the right. The cabling for the three transducers can be seen coming from above to the left side of the sphere.

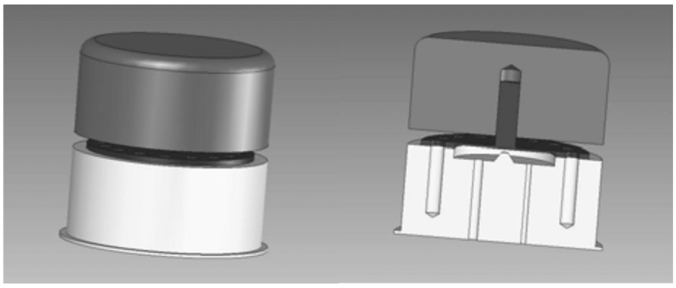


Figure 2. Schematic view of the 'non-resonant transducer' or inertial transducer used in the first commissioning runs (the two other transducers used each had a 53 g resonant mass): a metal membrane is bolted to a solid rigid cylindrical body, which has the microwave klystron cavity and the microstrip antenna, and is attached to the antenna surface (inside one of the sphere's nine holes). A $\sim$60 g mass is screwed to a threaded post coming from the membrane, causing the metal membrane to oscillate with a much lower resonant frequency than the sphere's quadrupole mechanical resonances, so it will stay motionless, like an inertial mass, when the spherical antenna is put into quadrupole oscillation. The relative movement between the motionless membrane and the klystron cavity little post top will cause the modulation of the microwave carrier signal inside the cavity.

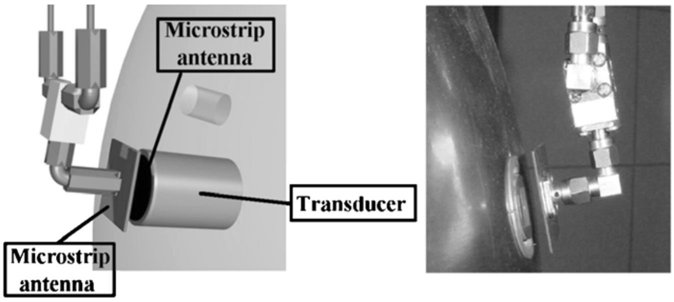


Figure 3. Detailed view of the microstrip pair of antennae: the microwave carrier signal is transmitted to the transducer and the modulated signal is received from it. The little box shown is a microwave circulator, which connects the coaxial cables to the microstrip antenna side hanging in front of the transducer. In doing so, no mechanical vibration is transmitted to the gravitational wave antenna through these coaxial cables.

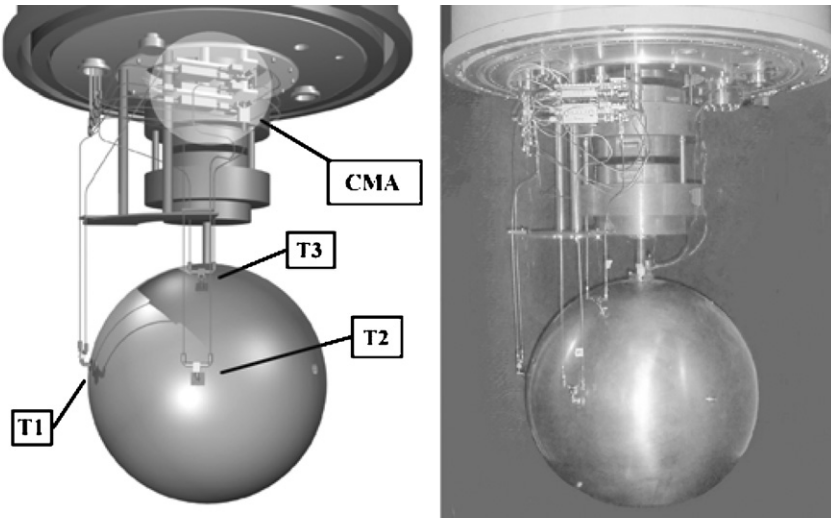


Figure 4. The position on the sphere surface of the three initial transducers can be seen. It is also possible to see the cabling lines going and coming from these transducers and the three cryogenic microwave amplifiers (CMAs) installed close to the bottom wall of the liquid helium reservoir.

resonant frequency leads to the loss of displacement sensitivity, and such a detuning needs to be avoided, if one wants to collect the data of any significance. Figures 4 and 5 show the position of the transducers, cryogenic amplifiers, thermometers, and also the schematic diagram of the transducer's electronic circuit.

The cooling down of the sphere started in the third week of August. The spherical antenna reached ∼4 K on 2 September. After tests at ∼5 K in vacuum, the system was adjusted and data started to be taken: 120 h of data in 7200 1 min files were taken for three transducers from 9 pm on the 8th to 9 pm on the 13th. The sphere temperature changed from 5 K to 6 K during this period. Many tests were done with different pump frequencies, amplitudes and gas pressure around the sphere. A second run was performed on 24 and 25 October around 55 K,

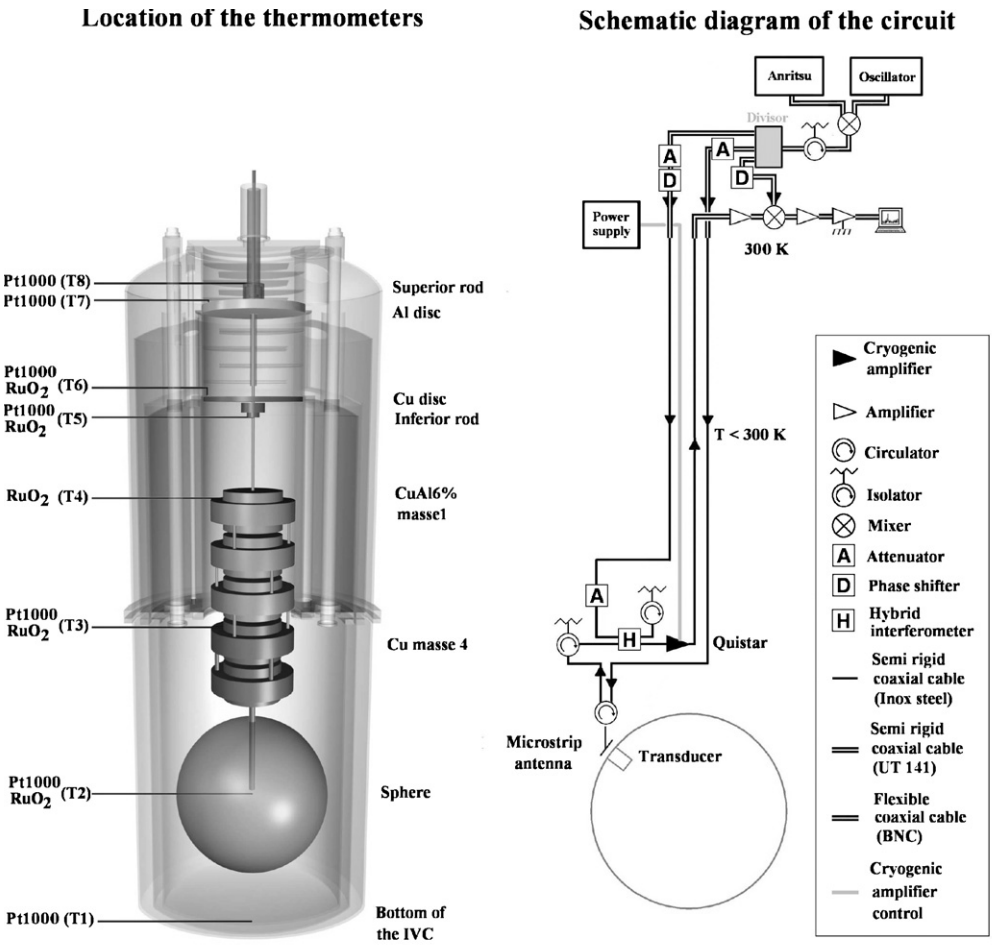


Figure 5. Location of the thermometers inside the detector and the schematic diagram of the transducer's electronic circuit (for one transducer).

during the warm up of the antenna. Figure 6 shows both the cooling down and the warm up temperature curves.

There was an electronic failure shortly before the beginning of the run which required improvising an analog-to-digital converter system. The substitute system, a PCI board from IOTech, model DaqBoard/2000, had many voltage spikes and saturations, which were not discovered until after these first commissioning runs (figure 7). Due to this problem, we were able to find only about 12 h of good data (10% of the total). The sampling rate was 10 k samples s^{-1} for all three transducers.

From these data we calculated the scaled strain noise, $K\tilde{h}$, in units of volts per meter times strain per square root of Hertz, where K is the unknown calibration constant, assuming we know the right transfer function. We also applied an optimal matched filter for very short burst signals, and a histogram of the filtered output of the number of events as a function of voltage square is shown in figure 8(*b*); this shows that at this level of sensitivity, we do not have problems with vibration or electromagnetic isolation. We do not see these voltage spikes

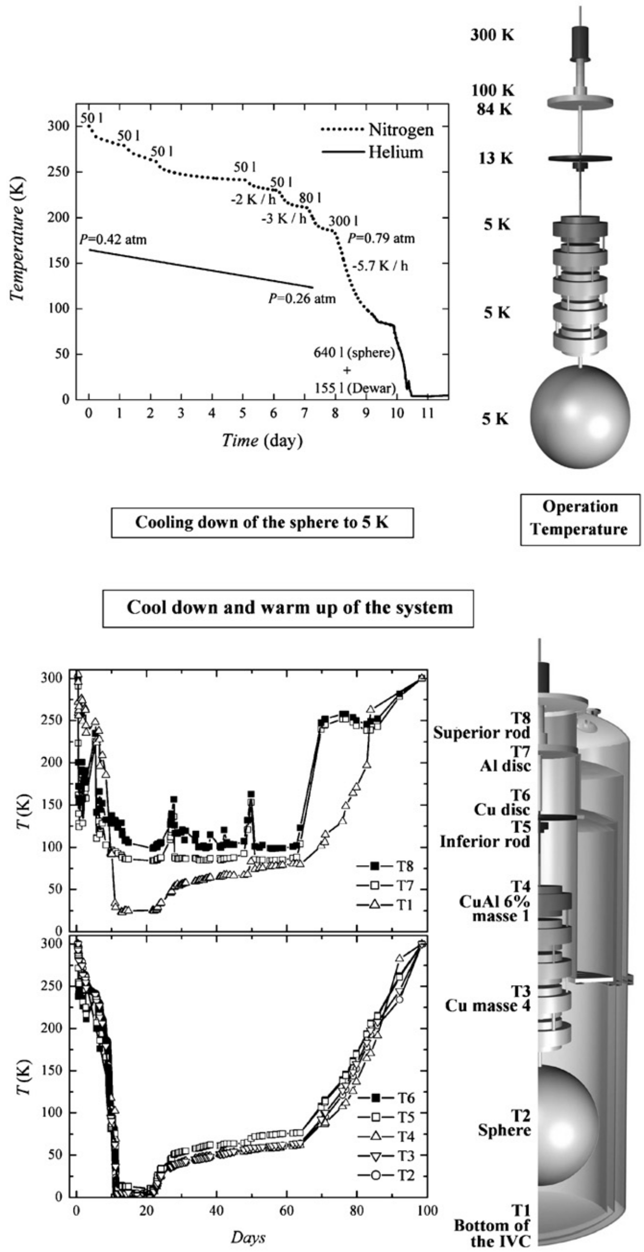
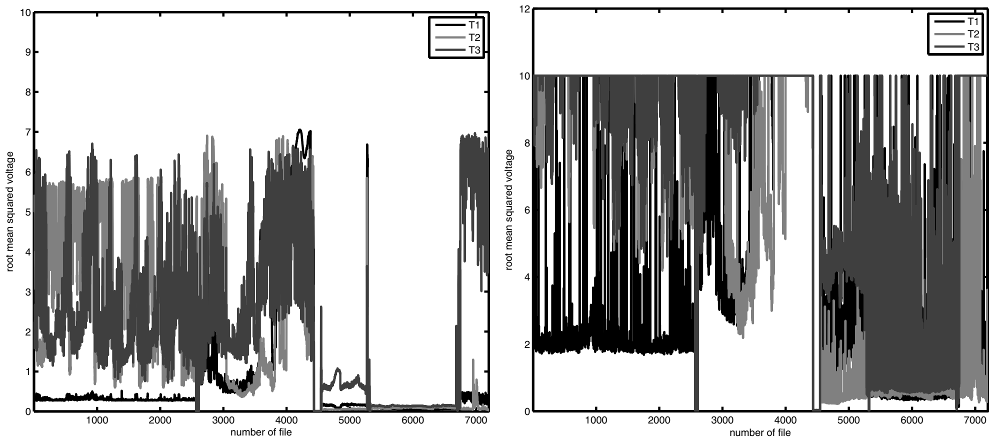
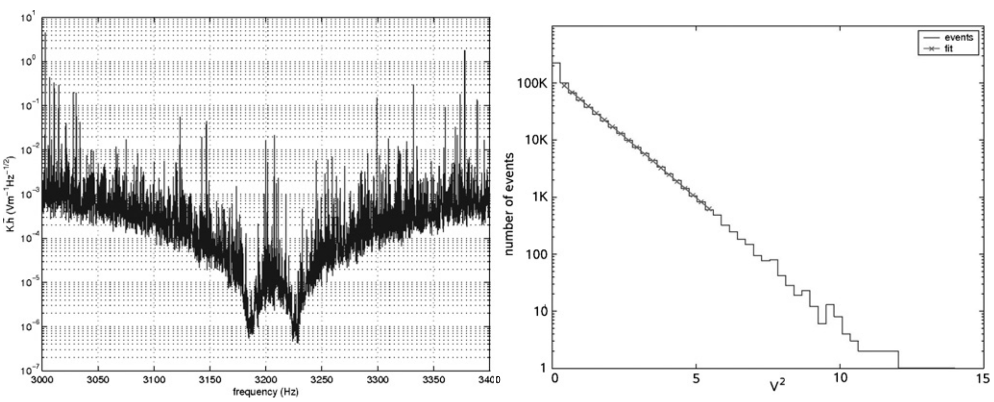


Figure 6. Cooling down and warm up of the system. The detailed cooling down curve of the sphere to 5 K can be seen on the top part of the figure. The exchange (helium) gas pressure was 0.42 atm in the inner vacuum chamber (ICV) at the beginning, and it dropped to 0.26 atm by the end of the 7th day. The overall temperature curve is shown on the bottom part of the figure. The first 8 days could have been compressed to about 2 days if the liquid nitrogen had been poured more frequently into the reservoir, not letting it run out. The run at 5–6 K lasted for about 12 days. After that, the temperature was risen naturally for the next 40 days, and then, the warm up was forced. According to the data of this run the 340 l liquid helium reservoir gives this detector autonomy of 9 days.



(*a*) (*b*)

Figure 7. Voltages for the 7200 1 min archives (120 h or 5 days of data): (*a*) root-mean squared (rms) voltages; (*b*) maximum voltages. Only about 10% (∼12 h) of the archives were free from these voltage saturations.



(*a*) (*b*)

Figure 8. Results from the first commissioning runs: (*a*) the scaled-strain amplitude spectral density. The calibration constant *K* was not measurable during these runs. (*b*) A histogram of the optimal linear filter output for a short burst signal, note the absence of outliers outside the Gaussian noise distribution.

and saturations in the test runs at room temperature any more, with our new VT1436 ADC from VXI Technology.

3. The new developments and future plans

Motivated by the presence of spikes and abrupt voltage variations in the data for the first commissioning runs, we tried to investigate all possible sources of signal variations. We ended up discovering that the pressure control system for the pneumatic air spring was showing hysteresis. A small air leakage was not corrected before enough pressure difference was built

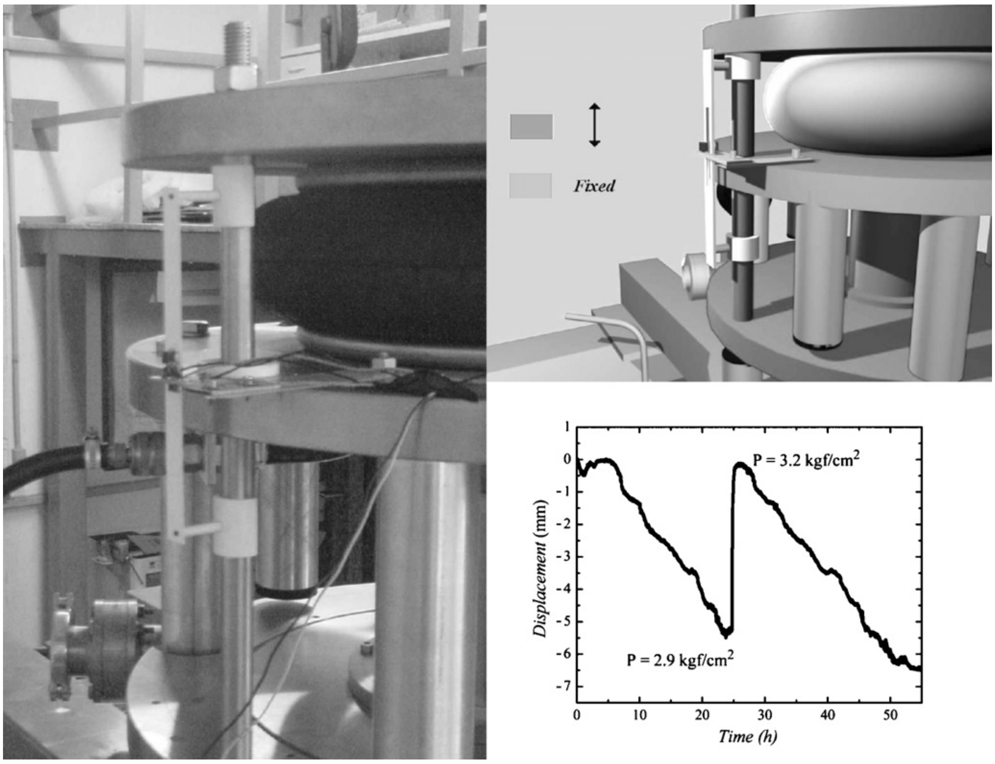


Figure 9. The pneumatic system that controls the vertical height of the sphere: a 'hysteresis' behavior (explained in the text) was found after installing an optical sensor to monitor the vertical movement of the sphere. This problem was fixed in order to avoid variation of the detector output signals.

up for the valve to act. Therefore, the pressure could fall from 3.2 kgf cm^{-2} to 2.9 kgf cm^{-2} in 24 h, as is shown in figure 9, before the system corrects itself abruptly. This was enough to change the vertical position of the sphere by 5–6 mm, causing the antennae of the pair of microstrip antennae to move vertically relative to each other by this much. We measured that this 5–6 mm relative displacement would change the modulated signal by about 20 dB (a factor of 10 in voltage) just because the microstrip antennae would change their response by that much. We have corrected this problem with a new valve and intend to change the design of the microstrip antenna pair to one lesser sensitive to relative motions between the two antennae. The hysteresis is negligible now, causing a 1 mm variation at most.

We are developing sapphire oscillators that will replace those we have been using thereby providing performance in phase noise and frequency stability. Figure 10 shows the setup for the tests of our sapphire cavity at 77 K in comparison with cavities borrowed from the University of Western Australia Metrology Group.

We also plan to install eight transducers in the near future, six of which are of the two-mode type and arranged according to the truncated icosahedron configuration [7]. The other two, which will be placed close to the sphere equator, will be mechanically non-resonant. In doing so, we want to verify if the Schenberg antenna can become a wideband gravitational wave detector through the use of an ultra-high sensitivity non-resonant transducer constructed

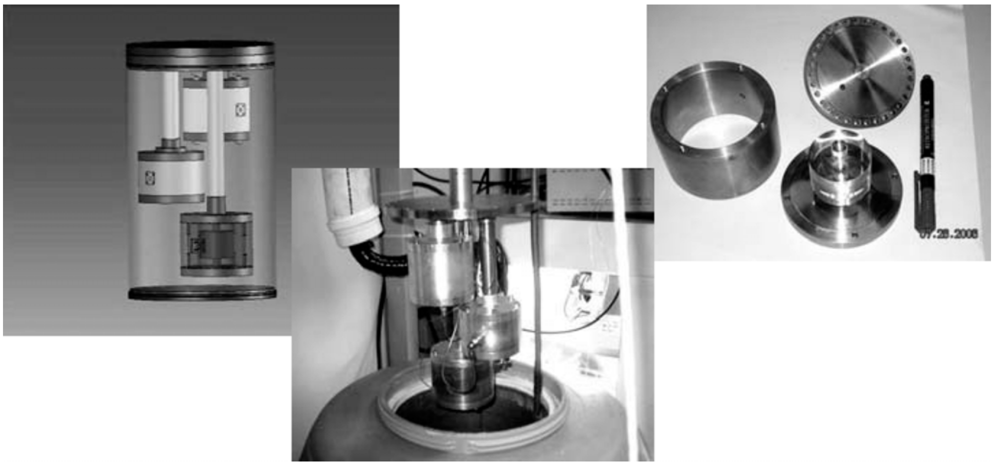


Figure 10. Schematic view and pictures of the setup for testing microwave sapphire cavities. These cavities will be used for a new generation of very low-phase noise oscillators that are being developed.

using the recent achievements of nanotechnology. Since the pioneering work of Paik in Stanford in the 1970s [11], cryogenic resonant-mass gravitational wave detectors use resonant transducers. Nanotechnology is opening new possibilities toward the construction of ultra-high sensitivity klystron cavity transducers. It might be feasible to construct TeraHz/micron parametric transducers in the near future. They would be so sensitive that there would be no need for multimode resonant transducers. The antenna would act as a broadband detector for gravitational waves. A spherical antenna, such as Schenberg or Mini-Grail, could add the advantage of wave position and polarity determination to this quality.

We are now preparing the system for the fourth (overall) cryogenic run, fixing several little problems that we detected in these first commissioning runs. This time a transducer for calibration will be used. After that, the next steps will be to make circuit cabling/wiring for at least a set of six transducers; to test the two-mode transducers (with silicon membranes); to test different superconducting cavities; to use sapphire oscillators at 77 K; to develop an ultra-high sensitivity non-resonant 'nano'-transducer [12].

Acknowledgments

We thank Warren W Johnson for helpful discussions and collaboration. This work has been supported by FAPESP (under grant nos. 1998/13468-9, 2005/00214-4 and 2006/56041-3), CNPq (under grant nos. 380237/04-0 and 308759/06-0), CAPES and MCT/INPE.

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