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E. Coccia:

ULTRACRYOGENIC GRAVITATIONAL WAVE EXPERIMENTS

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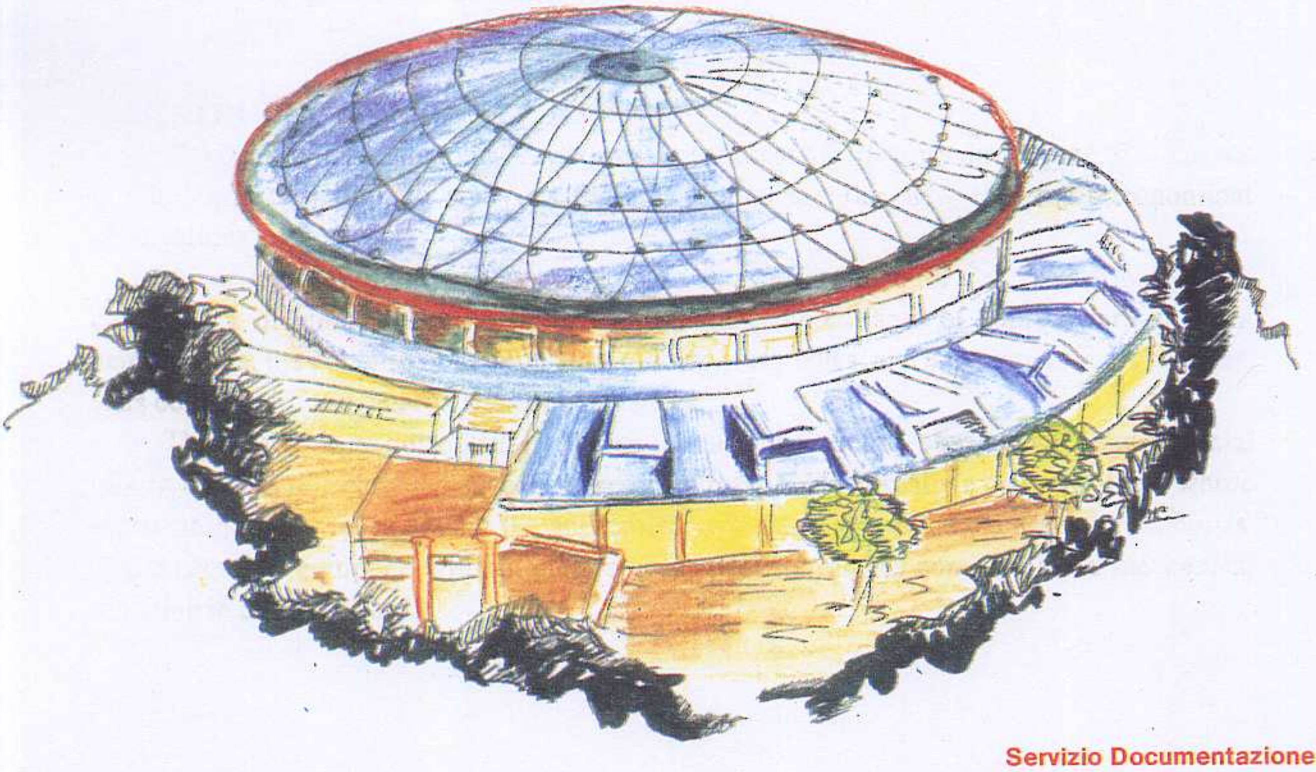

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ULTRACRYOGENIC GRAVITATIONAL WAVE EXPERIMENTS

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Abstract

Direct detection of gravitational waves, for physical or astrophysical study, is one of the great challenges of contemporary experimental physics. The problem is the extremely small size of the effect one wishes to measure. The advantages emerging from cooling a resonant antenna to very low temperatures are discussed in the first part of the lecture, together with the main requirements and features of cryogenic systems for gravitational wave experiments. In the second part we report on the ultralow temperature detector NAUTILUS. The goal of this new generation antenna is to detect bursts of gravitational radiation from sources located at distances up to the Virgo Cluster of galaxies. NAUTILUS is installed in the Frascati INFN Laboratories and should start operating at the end of 1993.

1 - INTRODUCTION

The goals of a gravitational wave (g.w.) experiment are to verify directly the existence of gravitational radiation, to study its features and to use this new tool for astronomical observations.

A variety of possible events could cause significant bursts of g.w. These include the coalescence of binary black holes, or neutron stars, the collapse of white dwarfs to form neutron stars, the collapse of neutron stars to form black holes, and supernova events in which stars collapse to form neutron stars or black holes.

The detector first developed by Weber [1] and subsequently used by other experimental groups consists of a carefully suspended resonant mass object, usually a cylindrical bar, whose vibration normal modes having the appropriate symmetry should be excited by g.w. bursts. The detector is equipped with an electromechanical transducer converting the mechanical vibration in an electric signal.

The problem of the detection of short bursts of g.w. has been clarified in its main aspects since many years [2–5]. The detector is assumed to be a single large mass quadrupole, and the energy absorbed ΔE_a, due to g.w., can be calculated by means of the cross section Σ, which for the most favorable polarization, direction of propagation and antenna mode of vibration (the first longitudinal one), takes the form [6]:

$$\Sigma = (8GM/\pi c)(v_s/c)^2 \tag{1}$$

where v_s is the sound velocity in the antenna material and M the mass of the antenna.

The energy absorbed can be written as:

$$\Delta E_a = f(\omega_R)\,\Sigma \tag{2}$$

where $f(\omega_R)$ is the spectrum energy density of g.w. at the resonant frequency.

The energy absorbed by the antenna must be large compared to the energy fluctuations in the detector. The energy noise can be written as the sum of three contributions:

$$\Delta E_n = kT\Delta t/\tau + kT_n\,(\beta\omega_R\Delta t)^{-1} + kT_n\,(\beta\omega_R\Delta t) \tag{3}$$

where T is the thermodynamic temperature of the antenna, τ the relaxation time of the mode of vibration, β is the ratio of the electromagnetic energy in the transducer to the total energy of the antenna, T_n is the noise temperature of the amplifier connected to the transducer and Δt is the measurement sampling time, much smaller than τ. There is an optimum value of Δt which minimizes the noise of the system: $\Delta t_{opt} = (\beta\omega_R)^{-1}$. Then the energy noise takes the simple form:

$$\Delta E_n = kT/\beta Q + 2kT_n \tag{4}$$

where $Q = \omega_R\,\tau$ is the quality factor of the mode of vibration.

If we use the parameters of a typical room temperature aluminium cylindrical bar (T=300 K, $Q=10^5$) equipped with a resonant capacitive transducer ($\beta=10^{-3}$) and a FET amplifier (T_n=1K), we find that we can observe with SNR=1 a spectral energy density at the Earth of the order of 1 J m^{-2} Hz^{-1}. This value corresponds to a collapse occurring in our Galaxy, at a distance of 5 kpc in which $10^{-2}\,M_0$ are converted in a millisecond burst. The g.w. amplitude h, which is of the order of the relative antenna displacement $\Delta L/L$, is in this case $h \sim \Delta L/L \sim 10^{-17}$. The discouraging expected rate of such collapses is of the order of 1 per 100 years. Thus the achievement of a reasonable rate of events implies to improve the sensitivity, for extending the observing range beyond our Galaxy and the Local Group of galaxies.

1.1 – The role of the thermodynamic temperature

It is straightforward from the above formulae that the low temperature is necessary to reduce the random thermal fluctuations kT in the antenna itself. The first term in eq. (3), $kT\Delta t/\tau$, is in fact due to the Brownian motion of the antenna, which is exactly analogous to the Nyquist noise of an LRC circuit, and represents the low frequency part of the black body spectrum of internal excitations. The mean energy of the fundamental mode of the antenna (determined from the low–frequency approximation to the Plank radiation formula) is simply equal to kT, but the effective noise is determined by fluctuations in this noise energy since the measurement of a gravitational wave is a measurement of the change in amplitude of the bar during the time interval Δt. The rate of fluctuation is related to coupling between the fundamental mode and the thermal reservoir. This coupling itself determines the acoustic loss of the bar. Thus the effective noise energy reduces as the relaxation time τ (or the quality factor Q) increases. The discovery [7] that at low temperature it is possible to take advantage of the steep increase of the quality factor Q for aluminium alloys convinced most of the experimental groups to use of these materials. In particular Al 5056 presents $Q \sim 10^7 - 10^8$ below 10 K [8].

The second noise term in eq. (3), $kT_n\,(\beta\omega_R\Delta t)^{-1}$, is due to the measurement process itself. It is simple additive or series noise due to the transducer and amplifier which read out the motion of the antenna. This noise has the familiar Nyquist form as experienced in most areas of electronic instrumentation. We can model the measurement system as an antenna coupled to a noiseless transducer, coupled to a noisy amplifier. Then this noise can can be attributed wholly to the amplifier, which has a noise temperature T_n, and therefore a noise energy of kT_n per unit bandwidth, which reduces as narrower the measurement bandwidth, that is as longer the sampling time, is.

The third term in eq. (3), $kT_n\,(\beta\omega_R\Delta t)$, is given by the noise due to the measurement process acting back onto the system being measured (back action noise). This noise causes fluctuations in the antenna in much the same way that the thermal reservoir of modes in the bar couples to the fundamental mode causing the Brownian noise of the antenna.

It is of paramount importance for the reduction of these noise terms that the low temperatures make it possible the use of the properties of superconductors to make very low noise parametric amplifier based on the Josephson effect (SQUID) [9], whose noise temperature can in principal approach the quantum limit ($T_n = \hbar\omega/k \cong 10^{-7}$ K for frequencies operation around 1 kHz).

From the optimized eq. (4) it is clear that a large value of β is necessary for reducing the noise. It is worth noting that a large vale of β is also necessary to get a large detector banwidth B, as $B \sim \Delta t^{-1}_{opt} = \beta\omega_R$. For instance, if β is close to 1, the antenna can have a bandwidth comparable with its resonant frequency.

Low temperatures improve the features of low loss capacitive transducers and allow the use of superconducting inductive transducers.

1.2 - The three generations of resonant detectors

The thermodynamic temperature of the antenna has been used to classify in different generations the g.w. experiments: the low cost and high reliability room temperature antennae developed by Weber in the '60s are said to be of the first generation. The 4.2 K cryogenic detectors developed in the '70s and beginning to be operationals in the '80s are of the second generation. In 1986 three of such cryogenic detectors (Rome, LSU, Stanford) have set a new upper limit on the intensity of g.w. bathing the Earth [10]. In 1989 The Rome antenna EXPLORER, cooled at 2.0 K with superfluid helium, reached the record sensitivity of $h \sim 7\ 10^{-19}$ [11,12], soon followed by the LSU detector ALLEGRO. These detectors can observe collapses taking place up to the Large Magellanic Cloud. The expected rate is of the order of 1 per 10 years.

Third generation experiments, making use of ultralow temperature tecniques, will operate soon with the goal of increasing the expected rate of events to several per year, reaching an instrumental sensitivity such as to observe burst sources occurring at distances of the order of that of the Virgo Cluster (2500 galaxies at ~19Mpc). We report in Table I the main features of the three generations of resonant antennae, with the minimum detectable value of the g.w. amplitude *h* for a conventional g.w. burst of 1 ms duration. In the last column it is reported the distance *d* from the Earth to the collapse in which 10^{-2} M_0, isotropically converted in g.w., would give the indicated value of *h*.

TABLE I – Main features of three generations of resonant g.w. detector.

Generation	T(K)	β	Q	T_{eff}(K)	h_c	d(kpc)
I	300	10^{-4}	10^5	10	10^{-17}	5
II	4.2	10^{-3}	10^6	10^{-2}	10^{-19}	50
III	0.1	10^{-2}	10^7	10^{-7}	10^{-21}	10^4

Likely events from Virgo cluster will cause a strain in a resonant bar of the order of 10^{-21}, which means an energy captured by the antenna as low as 10^{-31} J, corresponding to a temperature of the order of 10^{-7} K. In term of vibrational energy this is equivalent to one phonon. Sensitivity at the single phonon level is described as the quantum limit.

There are no fundamental limitations in reducing the Brownian noise term $kT/\beta Q$ of eq. (4) even below this level, while the noise kT_n of any *linear amplifier* has a fundamental limitation: cannot be less than $\hbar\omega_R$, because of the uncertainty principle.

The achievement of a quantum limited macroscopic oscillator is the challenge of the third generation ultracryogenic detectors. In order to reach this goal, the experimental parameters which determine the detector sensitivity must be pushed at the extreme limit of the existing conventional and quantum technologies.

The strategy of the Rome group consists in the use of the highest Q aluminium alloy as antenna material (Al 5056), the use of a resonant capacitive transducer [13] with $\beta \sim 10^{-2}$, the development of a dc SQUID amplifier [14] with noise temperature near to the quantum limit ($T_n \sim \hbar\omega_R/k \sim 10^{-7}$ K) and the cooling of the bar below 0.1 K temperatures using a ^{3}He–^{4}He dilution refrigerator [15].

In the years 1982–1984 a feasibility study was conducted to establish the technical possibility of the cooling of a multiton Al 5056 bar to millikelvin temperatures [16]. In 1986 INFN financed the Rome group project of an ultralow temperature antenna, NAUTILUS. In 1989/91 the detector has been assembled and tested to ultralow temperatures in the CERN laboratories [17]. In 1992 NAUTILUS has been installed in its operating site at LNF (INFN Laboratori Nazionali di Frascati) and is now ready to start a first period of observations. Two more ultralow temperature detectors are in the assembling or testing stage: one, AURIGA, at LNL (INFN Laboratori Nazionali di Legnaro), and another at Stanford University.

In the next section we report some considerations about cryogenics and gravitational wave experiments. In sec. 3 we present the results of the feasibility study for the third generation ultralow temperature detectors. In sec. 4 the NAUTILUS detector is described.

2 - CRYOGENICS AND G. W. EXPERIMENTS

The need of the low temperatures in the gravitational wave research was clear since the '60s, when Joe Weber was beginning the operation of a separated pair of room temperature g.w. antennas in coincidence.

The intriguing results of these measurements and the fascination of this field of research stimulated, among the others, the birth of the g.w. groups of Stanford, Baton Rouge (Louisiana) and Rome. From the very beginning (1970) the plan of these groups was to build cryogenic detectors, making use of the major improvements of the low temperature technique. Bill Fairbank, leader of the Stanford group, presented at that time an ambitious project for cooling at 3 mK a large antenna by combining the use of a ^{3}He–^{4}He dilution refrigerator and of the adiabatic demagnetization of a CMN salt.

In 1971 Weber cooled for the first time a 1.5 ton aluminium cylinder to liquid helium temperatures and.."*Immediately after cooling, a very large amount of noise was observed. Some of the excess noise appeared to be associated with internal structural relaxation of the cylinder. Some noise was due to acoustic coupling of high intensity noise associated with the liquid nitrogen and liquid helium system*" [18].

These considerations reflected the difficulties of operating a g.w. antenna at low temperatures, demonstrated by the twenty years efforts of several researchers in 4 continents. The problem was that for the first time a high Q resonant mass of various tons had to be cooled to 4.2 K or below, being free to move and isolated so well from the rest of the world to allow the detection of a displacement of the order of $\Delta L \sim 10^{-18}$ m.

In a low temperature system for a g.w. antenna, cryogenics and acoustic isolation requirements are strictly joined; they can be summarized as follows:

a) ensure a long operation time, with rare and short interruptions in the data taking for cryogenic manteinance;
b) ensure a constant and uniform temperature of the antenna; a stationary gaussian distribution of the amplitude of the bar vibrations, in absence of signals, is an important condition for a reliable antenna.
c) do not add extra mechanical noise, in order not to excite the vibrational modes at a detectable level;
d) preserve the inherent high mechanical quality factor Q of the bar.

The peculiar problem of a cryogenic g.w. experiment is to put a large resonant mass at the same time in good thermal contact but in very poor mechanical contact with an effective and long autonomy cooling source.

At 4.2 K a liquid helium bath surrounding the antenna vacuum-chamber serves as heat sink and some helium exchange gas is used to rapidly thermalize the detector. The gas is then pumped out before the data taking. The antenna temperature remains about 4.2 K as long as the vacuum chamber it is completely surrounded by the liquid helium. It is found that the source of mechanical noise constituted by the evaporating liquid helium must be attenuated by a factor 10^{-7} to not disturb the detector. This attenuation is provided by the suspension system, which is carefully designed to act as an efficient mechanical filter.

Temperatures as low as 0.8 K or 0.25 K can be reached by pumping on a bath of liquid ^{4}He or ^{3}He, rexpectively. In the first case the superfluidity of the liquid may help to fulfill the cryogenics and acoustic requirements.

Using the adiabatic demagnetization of a suitable paramagnetic salt much lower temperatures are possible. With cerium magnesium nitrate (CMN) 2 mK can be reached. Another method allowing to reach 1 mK is Pomeranchuk cooling, i.e. cooling by adiabatic compression of a liquid–solid mixture of ^{3}He [12]. These methods have a drawback: they are "one shot" rather than continuous methods of cooling.

The only method able to mantain temperatures as low as 4–10 mK continuously and in presence of large thermal inputs is ^{3}He–^{4}He dilution refrigeration [12].

As the temperature decreases below 1 K, the only effective cold transfer mechanism between the antenna and the cooling source becomes the conduction by solid. This makes the mechanical isolation from the cooling source of an ultralow temperature antenna a much more difficult task than for an antenna at liquid helium temperature.

3 - FEASIBILITY STUDY FOR MILLIKELVIN DETECTORS

A dilution refrigerator coupled to a g.w. detector must be silent and have enough cooling power to absorb the residual heat leak below 0.1 K and to cool the bar reasonably quickly. The thermal contact with the refrigerator will be on the central section of the bar, where requirements c) and d) are easier to fulfill.

3.1 –Thermal inputs

We have considered the thermal inputs on our antenna cooled at 0.1 K and surrounded by a shield at 1.0 K. Table II resumes the various contributions.

We have neglected all the time dependent heat leaks due to relaxation fenomena, mainly present in dielectric materials and depending strongly on magnetic fields.

Table II – Estimated thermal inputs on the antenna at 100 mK if the antenna is supposed surrounded by a shield at temperature about 1 K, at a residual pressure of 10^{-9} mbar, and suspended to it by a traditional central section cable of titanium.

Conduction by solid	1 μW
Conduction by residual gas	20 μW
Radiation	30 nW
Cosmic rays	20 nW

It turns out that the main thermal input come from the residual gases, which at a pressure of the order of 10^{-9} mbar may give a heat leak of the order of 0.3 nW/cm^2 (20 μW total).

There are no systematic studies of the residual heat leak in ultra–low temperature apparatuses, the knowledge of them being mainly based on conclusions from trial–and–error improvement work. Some considerations present in the specialised literature [20] indicate an upper limit of 1 nW/cm^2 for the residual heat leak below 0.1 K, which is compatible with our estimates. 1 nW/cm^2 means 60 μW of total thermal input on the antenna. This figure determines the minimum cooling power of the refrigerator at those temperatures.

A further reduction is obtainable surrounding the antenna with shields cooled below 1K.

3.2 - Thermal gradients

The antenna material Al 5056 becomes superconducting at the critical temperature T_C=0.925 K [16]. Consequently the thermal conductivity κ becomes very low at millikelvin temperatures. The experimental data follow below 1 K the law:

$$\kappa \approx 2.5\, T^{-3}\ [\, W\, m^{-1} K^{-4}\,]$$

Because of the low thermal conductivity, at very low temperatures the residual heat leak may cause a very large thermal gradient along the antenna, which does not depend on the performance of the refrigerator. The mixing chamber of the dilution refrigerator will be in fact in contact with the central section of the cylindrical bar, keeping it at a certain temperature, while the ends temperature (which is also the transducer temperature) will stabilize at some warmer temperature, depending on the amount of thermal inputs on the antenna. The uniform thermalization of the antenna at 100 mK, within 20%, is compatible with a maximum heat leak of 10 μW. Uniform cooling at 50 mK would require an heat leak not larger then 1 μW. These heat leaks also express the required values of the refrigerator cooling power at those temperatures.

3.3 - Cooling times

The thermal time costant of a bar of mass M, length L, cross section A, density ρ, specific heat c and thermal conductivity κ, cooled from one end, is:

$$\tau_c = \frac{M c}{\kappa A/L} = L^2 \rho \frac{c}{\kappa}$$

For a 3 m long Al 5056 bar in the temperature range 4.2K – 0.05K τ_c is of the order of a few hours, indicating a reasonable cooling time.

Using the measured thermal properties of the antenna material [16] and numerically integrating the heat diffusion equation, the exact time dependence of the temperature of a 2300 kg Al 5056 bar, 3 m long, 0.6 m of diameter, thermally anchored to a dilution refrigerator at the middle section, can be computed [21]. The antenna can be supposed initially thermalized at 1 K, and put, at the time t = 0, into contact with 0.1 K thermal ground. The results of these calculations have been reported in refs. 16 and 21: we recall here that six hours are necessary to reach 0.110 K and the heat flux is, apart for an initial interval of some tens of minutes, well below the cooling power reachable by commercial dilution refrigerators.

These estimates indicate that the uniform cooling below 0.1 K of a large antenna is possible. The cryogenic apparatus must be consequently designed with the main goal of reducing the total heat leak to the antenna at the level of few μW. A configuration of various intermediate shields around the antenna, at temperatures below 1 K, is useful to cryopump the residual gases. As a consequence of the high thermal insulation, the required cooling power of the dilution refrigerator is quite low (as low as the residual heat leak). It is clear that the refrigerator has to be specially designed to constitute part of a large cryostat and cool intermediate shields.

3.4 – Thermal contact and mechanical isolation

The possibility of measuring g.w. amplitudes of the order of 10^{-21} (which means an antenna displacement of the order of 10^{-21} m) imposes severe limits on the sources of mechanical vibration present in the experimental apparatus. For instance the boiling of liquid helium in the cryostat container of the 4.2 K antennae must be attenuated of at least a factor 10^{-7} by mechanical filters placed between the helium container and the antenna. In the new milliKelvin criostats this noise source is suppressed by the use of several shields below 1 K, which constitute intermediate masses for the needed mechanical filters between the noise source and the antenna. Only the new source constituted by the refrigerator should become relevant.

An operating dilution refrigerator works with a circulation of almost pure ^{3}He gas. The circulation is sustained by a room temperature leak tight mechanical pump. Both the mechanical noise of the pump, transmitted along cables and pipes, and the noise due to the ^{3}He circulation are carried to the mixing chamber, which is the coldest part and has to be in good thermal contact with the aluminium bar.

The main experimental problem is to provide at the same time an excellent vibration isolation and a good thermal link between antenna and mixing chamber.

The simplest design is that of suspending the bar with the traditional central section cable whose ends are thermally anchored to the mixing chamber of the dilution refrigerator (see Fig. 1).

Let us find a precise requirement for the refrigerator mechanical noise source $S_R[\mathrm{mHz}^{-1/2}]$, applied at the upper ends of the suspension cable. The resulting excitation of the antenna mode of vibration is [22]:

$$x_0 = S_R\, Q\, A\, \lambda\, \Delta\nu^{-1/2}$$

where x_0 is the amplitude of vibration of the antenna ends, Q is the quality factor and $\Delta\nu$ the bandwidth of the antenna resonance, A is the attenuation provided by the suspension and λ is an adimensional factor which expresses the ability of the external vibration to excite that vibrational mode and depends on the geometry of the contact between suspension and antenna. For instance if we want to observe amplitudes x_0 of the order of 10^{-20} m, it turns out that S_R has to be kept below $10^{-19}\ \mathrm{mHz}^{-1/2}$ around 1 kHz.

This appears as the major experimental problem of the third generation detectors.

In order to minimize S_R, the flow of ^{3}He in the heat exchangers and in the mixing chamber must be minimized. Low flow causes low cooling power. The resulting indication is to use a dilution refrigerator with high cooling power (say of the order of 1 mW at 100mK) when ^{3}He is fully circulating (generally some millimoles/s), so that it still has the needed few μW when set in a minimum flow condition. Moreover the vibrations trasmission can be damped using soft multiwires copper braids as thermal paths between the refrigerator and the antenna.

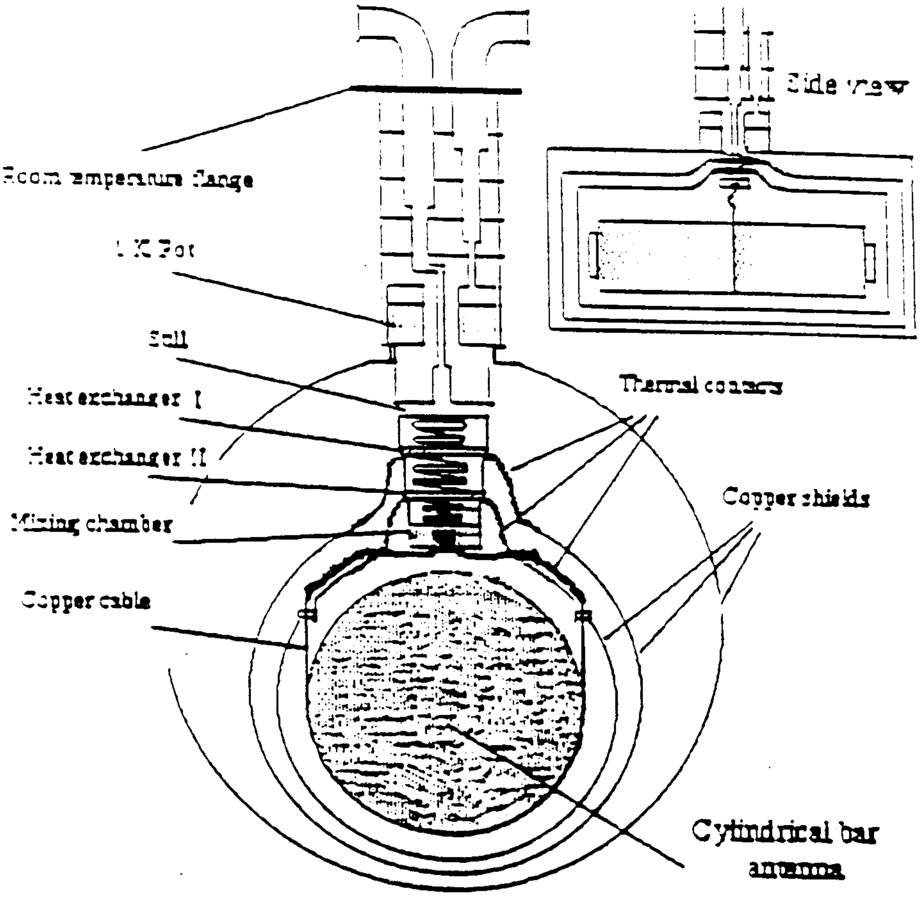

FIG. 1 – Schematic layout of the dilution refrigerator and its connections to the cylindrical bar and to the three copper shields. The shields are suspended each other and are cooled by different stages of the refrigerator. The external shield (2090 Kg) is cooled to 1.3 K by the 1 K pot, the heat exchanger I cools to about 350 mK the intermediate shield (860 Kg) and the heat exchanger II cools to about 180 mK the internal shield (800 Kg) surrounding the bar. The bar (2350) Kg is cooled to below 100 mK by the mixing chamber, via the copper cable suspension.

3.5 – Feasibility study conclusions

i) The cooling of a 2.3 ton Al 5056 bar, 3 meters long, below 0.1 K temperatures is possible using a ^{3}He–^{4}He dilution refrigerator: a cooling power of the order of 100μW is sufficient to thermalize the bar at 0.1 K in half a day time.

ii) A multishield configuration at temperatures below 1 K is necessary in order to:
   a) reduce the heat leak to few μW for obtaining the thermalization of the whole bar uniformly at temperatures below 0.1K.
   b) have a sufficient number of intermediate masses for variuos mechanical filters needed to isolate the antenna from the noise of the boiling liquid helium.
   c) allow the refrigerator to work with a minimum ^{3}He flow, in order to reduce the influence on the antenna of the acoustic noise coming from the heat exchangers and the mixing chamber.

These results determined the design of the NAUTILUS antenna.

4 - NAUTILUS

In 1986 INFN financed the Rome group project of the ultralow temperature antenna NAUTILUS and in 1989/91 the detector was assembled and tested to ultralow temperatures in the CERN laboratories [17].

In 1992 NAUTILUS has been installed in its operating site at LNF (INFN Laboratori Nazionali di Frascati), where it has been placed on a special platform which can rotate for the proper orientation of the detector with respect to either an array of detectors or even a fixed source.

NAUTILUS is now ready to start a first period of observations.

4.1 - The cryogenics

The general layout of the cryogenic apparatus is shown in Fig. 2 [17]. We recall here that the relevant feature of the cryostat is its central section, which is shorter than the cylindrical bar antenna itself. This section contains two helium gas cooled shields, the liquid helium (LHe) reservoir (2000 liters of capacity), three OFHC copper massive rings and, through the top central access, a special ^{3}He–^{4}He dilution refrigerator [23]. End caps are fastened at each stage of the cryostat to complete the seven shields surrounding the bar. The shields are suspended to each other by means of titanium rods and constitute a cascade of low pass mechanical filters. The overall mechanical vibration isolation at the bar resonant frequency (about 900 Hz) is of the order of –260 dB.

The first copper shield is thermally anchored to the 1 K pot of the refrigerator. The intermediate and inner shields are in thermal contact with two step heat exchangers of the dilution refrigerator; the mixing chamber [24] cools the bar by means of an OFHC copper rod wrapped around the bar central section [25]. The thermal path in these cases is constituted by soft multiwire copper braids, in order to minimize the transmission of mechanical vibrations to the bar (see Fig. 1) [26]. We recall here that the bar has a mass of 2350 kg, length of 3 m and diameter of 0.6 m.

Fig. 3 shows the bar temperature during the first cool–down. About three weeks were needed to reach 77 K, using 8000 liters of liquid nitrogen, and about one week to achieve 4.2 K, using about 5000 liters of LHe. We then kept the bar temperature in the range 4.2–8 K for about two weeks, to perform various tests.

When we started the ultralow temperature cooling, we filled the 1K pot with LHe at low pressure and started to condense and circulate the ^{3}He–^{4}He mixture in the dilution refrigerator. After three days the calibrated Ge thermometers indicated a temperature of 95 mK on the bar end face and of 63 mK on the mixing chamber. As far as we know, it was the first time that such massive bodies were cooled at these very low temperatures.

The observed features of the cooling agree with the model [21]. From the measured thermal gradient between the mixing chamber and the bar end (about 30 mK) we deduce an upper limit of 10μW for the antenna heat leak (corresponding to 1.7 μWm^{-2}).

The overall LHe evaporation rate at regime was 50 litres/day.

We remark that in this run we could not optimize the ^{3}He flow, because of an electrical short in the still heater, so that all of the above results were obtained with a reduced refrigerator cooling power. We think that a bar temperature of about 50 mK is possible.

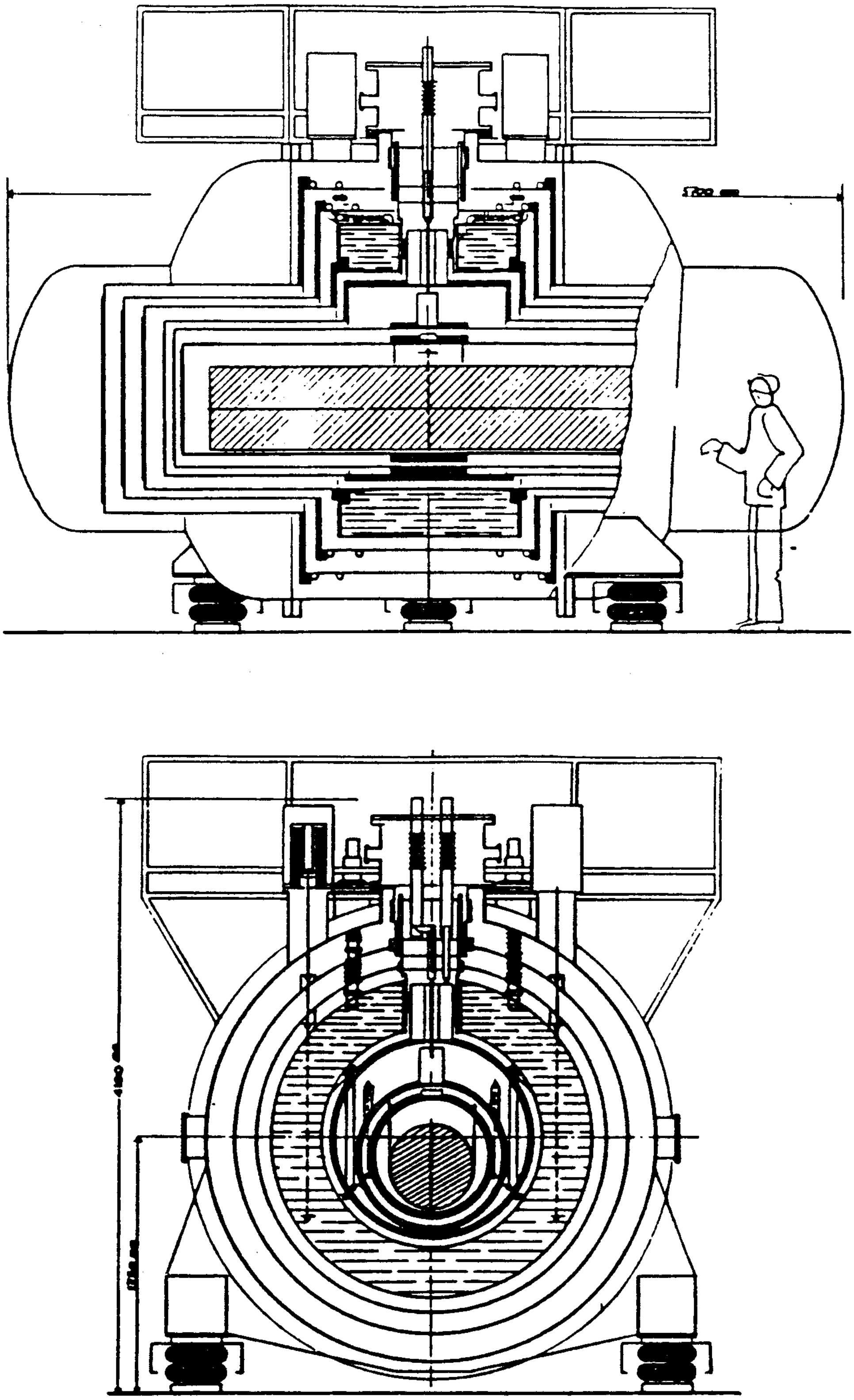

FIG. 2 – Layout of the NAUTILUS antenna.

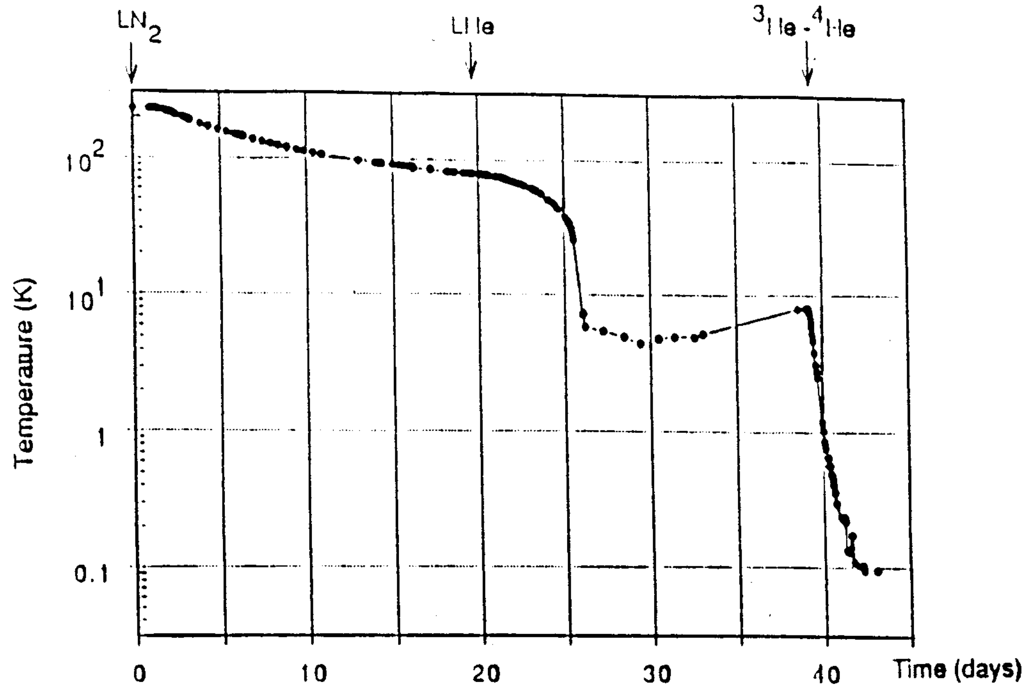

FIG. 3 – Temperature of the cylindrical bar versus time, The arrows indicate the main cryogenic operations, described in the text.

4.2 – Transducer and SQUID amplifier

NAUTILUS is equipped with a resonant capacitive transducer and a dc SQUID preamplifier (see Fig. 4), following the electrical measurement configuration developed for the EXPLORER detector [12], in operation at CERN.

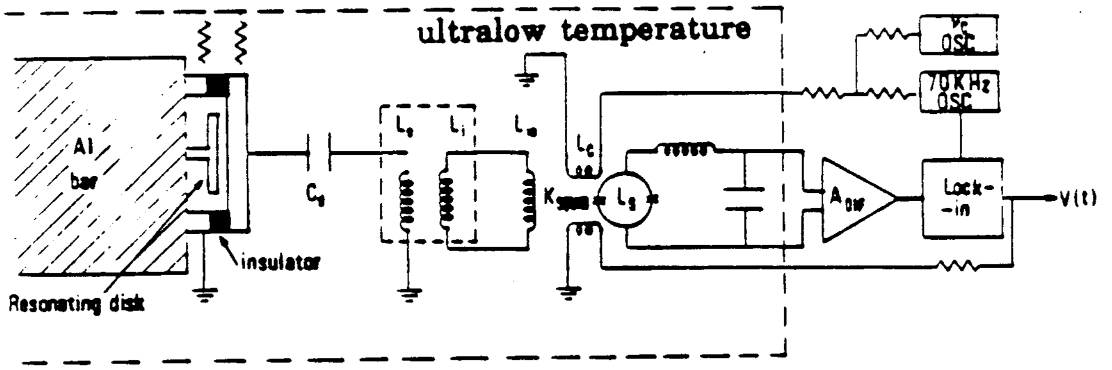

FIG. 4 – Electrical scheme of the experimental apparatus. The vibration of the bar are converted into electrical signals by a capacitive transducer, resonating at the antenna frequency in order to improve the energy transfer from the bar to the electronics. Bar and transducer form a system of two coupled oscillators. The signals are applied to the input coil of a dc SQUID amplifier by means of a superconducting transformer, which provides the required impedance matching. The output signal from the SQUID intrumentation contains the informations on the vibrational state of the antenna and can be properly processed.

The vibrations of the bar are converted into electrical sygnals by a capacitive transducer resonating in its first flexural mode at a frequency ν_t equal to that of the bar: $\nu_t=\nu_b=916$ Hz, in order to improve the energy transfer from the bar to the electronics. The transducer is schematically shown in fig.4 and has been described in refs [12,13]. In order to have a high Q, the transducer is made of the same material of the bar and is very carefully clamped on the bar end face. When charged with a constant electric charge q, the voltage v(t) across its plates changes with time as the mean distance d(t) between the plates:

$$\delta v(t) = (q/\varepsilon_0 S)\ \delta d(t)$$

Bar and transducer form a system of two coupled oscillators with resonant frequencies

$$\nu_+ = \nu_b(1+ \mu^{1/2}/2)$$

$$\nu_- = \nu_b(1- \mu^{1/2}/2),$$

where

$$\mu = \mu_t / \mu_b$$

is the ratio of the reduced mass of the transducer m_t to the reduced mass $m_b = M/2$ of the bar The transducer capacity C_t is of the order of 4 pF, the plates having about 18 cm diameter and a gap of the order of 50 μm. The applied voltage is around 300 V, which means an electrical field of about 5 10^6 V/m between the plates.

The voltage signal $\delta v(t)$ needs to be amplified. This is done with a dc SQUID amplifier.

The dc SQUID is perhaps the most sensitive low frequency amplifier yet invented, at least for low impedance sources, and for that reason it plays an important role in g.w. detectors.

Our dc SQUID, described in refs [12, 27], is a planar device with a multiloop geometry, it has very low intrinsic noise and good coupling with the external world. Its inductive input impedance is of the order of $\omega L_s \sim 10^{-2}\ \Omega$, since the input coil has inductance $L_s = 1.6$ μH. Since the output impedance of the transducer is much larger ($1/\omega C_t \sim 5\ 10^4 \Omega$), the signals are applied to the input coil of the dc SQUID by means of a special superconducting transformer, which provides the impedance matching. The output voltage is proportional to the magnetic flux across the SQUID.

The SQUID is biased with a dc current and a signal at the modulation frequency ν_m of about 70 kHz, applied through a coil. The output voltage is applied to a differential input low noise FET amplifier through an LC resonant circuit tuned at ν_m which provides the proper noise impedance matching. This is followed by a lock–in driven at ν_m whose output V(t) is fed back to the SQUID for stabilising its operating point. For monitoring continuously the SQUID operation, a reference magnetic field is applied at a frequency ν_c through the same coil used for the moulation. The experimental wide band noise, expressed in terms of magnetic flux, is $\phi_n \sim 1{,}5\ 10^{-6}\ \phi_0/\mathrm{Hz}^{1/2}$ (unilateral), where $\phi_0= 2.07\ 10^{-15}$ Wb is the flux quantum.

The output signal V(t) from the SQUID instrumentation contains the informations on the vibrational state of the antenna and can be properly processed.

4.3 - Vetoes

As a consequenece of its quadrupolar nature, a gravitational wave can excite only the odd longitudinal modes of a resonant bar. Then the output of a transducer monitoring the second longitudinal mode of the bar constitutes a powerful intrinsic veto, able to discriminate the gravitational nature of the excitation. For this reason a second resonant transducer , tuned at 1800 Hz, with a second SQUID amplifier have been placed at the free end of the NAUTILUS bar.

The detector is completed with seismic, electromagnetic and cosmic rays veto systems.

The necessity of a cosmic rays detector is due to the fact that extensive air showers or energetic single particles (muons or hadrons) interacting in the antenna may produce signals whose rate increases with the increasing sensitivity of the antenna to g.w. [28]. For instance 1 cosmic ray event per day is estimated for NATILUS having $T_{eff} \sim 1$ mK. This rate increase to 10^3 when $T_{eff} \sim 1$ μK and to 10^5 if the quantum limit $T_{eff} \sim \hbar\omega_R/k \sim 0.1$ μK is reached.

The veto system consists of two layers of streamer tubes for a total of 102 counters. The first layer (6x6 m^2) is located on the top of the cryostat. The second layer (6x2.5 m^2) is under the cryostat. The system detects about 50% of the single track events leaving in the antenna more than 10 Gev (corresponding to $T_{eff} \sim 1.5$ μK). For extensive air shower the efficiency is almost 100%.

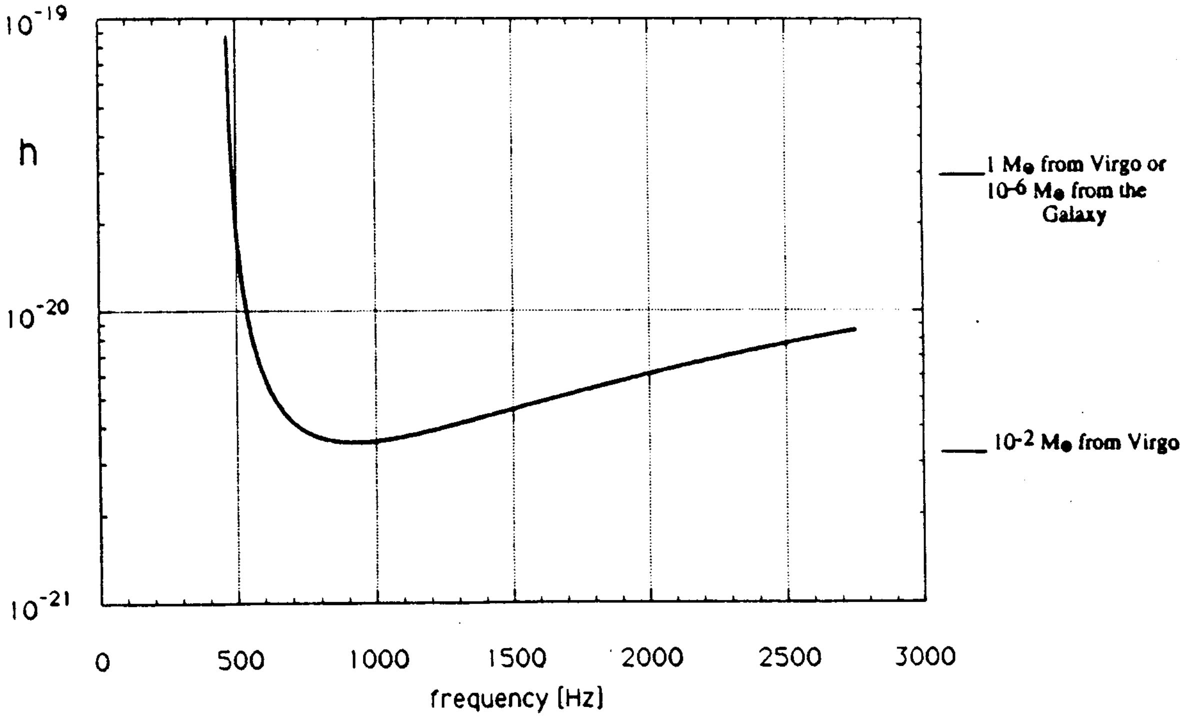

FIG. 5 - Planned sensitivity of NAUTILUS to g.w. pulses. It is assumed that the pulse consists of one sinusoidal cycle with the frequency reported in the abscissa. On the right we report the expected g.w. amplitudes at the Earth corresponding to the conversion of solar masses into g.w. isotropically emitted from the indicated distances.

4.4 - Sensitivity

The effective noise temperature in the first run, end 1993, should be of the order of 800 μK. To obtain a sensitivity near the quantum limit (fraction of μK) requires the transducer to be better matched to the SQUID and the SQUID amplifier itself to be of quantum limited sensitivity. Intensive work is in progress in this direction.

In Fig. 5 the pulse sensitivity of NAUTILUS at the quantum limit is shown.

5 - FUTURE DEVELOPMENTS

5.1 - The quantum limit problem

It has been realized that the quantum limit is not a limit at all [29]. This limit arises because of the way in which we make our measurements. It arises because we measure using a pair of quantum-mechanically conjugate observables. These are conventionally denoted X_1 and X_2. Since they are conjugate, the maximum sensitivity is limited by the uncertainty principle

$$\Delta X_1 \Delta X_2 > \hbar/m\omega$$

Usual linear devices lead to the quantum limit, because they measure X_1 and X_2 symmetrically. The uncertainty in each variable is equal and $\Delta X_1 = \Delta X_2 = (\hbar/m\omega)^{1/2}$.

If a phase sensitive transducer is used, sensitive to X_1 but insensitive to X_2, then the uncertainty principle is satisfied for $\Delta X_1 << \Delta X_2$. A signal is then observed by making high resolution measurements of X_1, and the resolution can allow the detection of energies less than $\hbar\omega$. Back action forces (which in fact can be used to illustrate how the uncertainty principle arises) feed into the unmeasured X_2 coordinate, while observing X_1.

The development of the so-called "quantum non demolition" (QND) devices involves a major technical effort.

In order to push the NAUTILUS sensitivity towards and possibly beyond the quantum limit, new non linear schemes of amplification and electromechanical transduction are currently under investigation.

5.2 - Gravitational wave observatories

It is crucial for the unequivocal detection of g.w. that various antennae of comparable sensitivity and bandwidth operate in continuous and well coordinated coincidence. This is also necessary for a complete reconstruction of the incoming g.w., i.e. the determination of amplitude, polarization and direction of propagation of the burst.

Proposed strategies of detection involve the use of an array of 6 properly oriented ultracryogenic bars to recognize the distinctive properties of the Riemann tensor of the gravitational perturbation [30].

It is natural to plan in the near future coincidences between NAUTILUS and the ultralow temperature antennae AURIGA, in preparation at LNL, and the one in preparation at Stanford University.

At present the advantages of an omnidirectional g.w. observatory constituted by two spherical resonant detectors are under study.

The future operation of the large interferometric g.w. antenne LIGO and VIRGO, which sensitivities extend to low frequency down to 10 –100 Hz, opens interesting perspectives of measurements in coincidence between complemetary detectors: resonant and non resonant antennae.

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