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Status of the VIRGO experiment

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Abstract

The VIRGO experiment was approved in September 1993. The goal of the French-Italian collaboration is to detect Gravitational Waves using a 3km arm-length Michelson interferometer. The construction of this detector, which will be installed in Pisa, is under way. The experiment is planned to take data, in a large bandwidth (10Hz-10kHz), at the beginning of year 2000 with nominal sensitivity close to $h = 3.\ 10^{-23} / \sqrt{Hz}$.The motivations, detection principle, main sources of noise and status of the experiment are presented.

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Introduction

Gravitational waves are emitted when a massive system with non-zero quadrupolar moment undergoes an acceleration(1). They were predicted to exist by Einstein(2) already in 1916-1918 and have still not been directly detected. Thanks to the work of Taylor(3) interpreted by Damour and Deruelle(4) on the evolution of the pulsar PRS1913+16, we have now solid "indirect" evidence for their existence .

The discovery of gravitational waves will not be only a test of general relativity , it will also give a better understanding of the gravitational force. Since gravitational waves are real gravitons, their detection will be a first step towards the evidence of the gravitational force intermediate boson. Astrophysicists share also another motivation for the direct detection of gravitational waves. Their arguments are that:

-1) unlike electromagnetic waves, gravitational waves are not absorbed by matter,

-2) all our knowledge about the universe is based on information carried by E.M. waves (except a few ν events),

-3) gravitational waves are expected to be emitted from places where the density of matter is large (places from where electromagnetic waves cannot escape). Therefore the detection of gravitational waves will give us a completely new picture of the universe.

The first goal of the VIRGO experiment is to detect gravitational waves. The next step will be to perform, in conjunction with other similar detectors, more precise measurements (i.e. the mass and helicity state of the graviton) and start gravitational wave astrophysical observations.

Generalities

We recall here a few relevant features of the gravitation theory, more details can be found in reference(1). When a gravitational wave propagates through space, the metric is perturbed. In the case of weak field, we have:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad \text{with} \quad h_{\mu\nu} << 1$$

where $h_{\mu\nu}$ is the gravitational perturbation to the flat space-time Minkowski metric $\eta_{\mu\nu}$. This translates into a change ΔL of the distance L between two free masses. When the gravitational wavelength is small compared to L one has $\Delta L = \frac{hL}{2}$.

When a massive system emits an amount of energy E_g as gravitational waves, the corresponding order of magnitude of the h value at a distance r is given by[5]:

$$h \approx \frac{R_S}{r} \quad \text{with } R_S = \text{Schwarzschild radius corresponding to } E_g :$$

where $R_S = \frac{2GM}{c^2}$, $M = \frac{E_g}{c^2}$ and G is the Newtonian gravitational constant.

Like electromagnetic waves, gravitational waves are predicted to have two states of polarisation: $h+$ and $h\times$, the angle between the two states being 45^0 (instead of 90^0 in the electromagnetic case). In the frame of the theory of General Relativity gravitational waves propagate only in an helicity state of 2.

Sources of gravitational waves

With today's technologies, it seems hopeless to achieve an Hertz-like experiment (emission and reception in the laboratory) because any conceivable Earth-based apparatus cannot radiate enough power to produce detectable gravitational waves. Astrophysical processes, which involve large masses suffering large accelerations, are the expected sources of detectable gravitational radiation. Three main types of sources are considered;

1) explosion-like phenomena: supernovae or black holes formation. These events are expected to produce very short bursts of gravitational radiation, whose amplitude and time evolution are very poorly known[6]. These poor predictions are a direct image of our ignorance about the degree of asymmetry of the collapse (a perfectly symmetric collapse does not radiate) and about the physical processes involved. Some predictions gave a typical value of $h \approx 10^{-21}$ for a supernova exploding at the centre of the Virgo cluster (1000 galaxies): the VIRGO experiment aims at a sensitivity good enough to detect such events, hence its name. A few such events are expected per year.

2) Periodic sources: slightly asymmetric pulsars are also expected to radiate gravitational waves. Their amplitude is predicted to be small because the radiated power tends to symmetrize the pulsar rotation. A few pulsars are predicted to emit gravitational waves in the frequency range 10 to 100Hz (double of the optical frequency). A typical prediction for the Crab pulsar emission gives values ranging from $h \approx 10^{-24}$ to $h \approx 10^{-28}$.

3) Semi-periodic sources: they are the final state of the coalescence of a binary system[7]. From the observed properties of the 1913+16 pulsar and of some other binary systems, one can infer that coalescences, within the VIRGO sensitivity, occur a few times per year, emitting bursts of gravitational radiation. These bursts whose amplitude and frequency behaviour are completely predictable may well be produced within the VIRGO experiment detection sensitivity.

Virgo, interferometric detection

The full description of the VIRGO detector has been given elsewhere(8), here only the main features, improvements with respect to the proposal or new status of key points will be discussed.

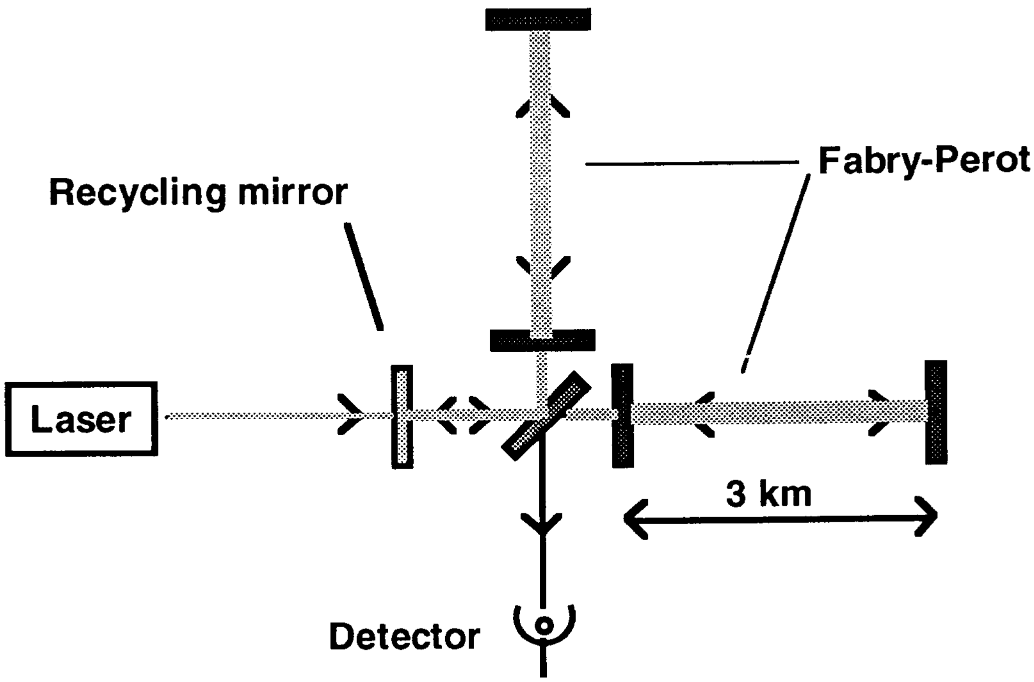

Fig-1 Principle of the VIRGO interferometer

The principle of the detector is sketched on Fig.1. A 3km arm-length Michelson interferometer, with suspended mirrors (test masses), is used. The phase difference $\Delta\varphi$ between its two arms is "magnified" using a Fabry-Perot cavity of finesse $\mathcal{F}=50$ in the arms. Aiming for detection sensitivity of $h \approx 3.10^{-23} / \sqrt{Hz}$, VIRGO is a very delicate experimental challenge because of the competition between various sources of noise and the very small expected signal.

The interferometer being tuned on the "dark fringe", the signal to noise ratio is mainly limited, in our range of sensitivity, by:

- the photon counting noise (shot noise)
- the refractive index fluctuations in the interferometer arms
- the fluctuations of the input laser amplitude and frequency

- the vibrations of the critical optical components

Photon counting

The shot noise corresponds to the Poisson statistical fluctuations of the photons number in the light beam, its relative effect decreases like $1 / \sqrt{P}$ where P is the beam power. This noise can be decreased by using high efficiency photo detectors and by increasing the laser light power. Unfortunately, the light power cannot be increased at will, mainly for two reasons:

1) the stabilisation of a very high power laser becomes unmanageable. A practical limit in our Nd:YAG laser case is 20W. To overcome this difficulty, we will "recycle" the light which is reflected from the interferometer. This is performed by a semi-transparent recycling mirror (see Fig.1) which is carefully kept in position such as to be in-phase with the incoming light beam.

2) The energy which can be stored in the Fabry-Perot cavities is limited due to the absorption in the mirrors. The very high quality mirrors required for this interferometer are now only available in very small dimension. A special R&D program is undertaken in Lyon to reach their ultimate specifications which have been optimised, on the basis of complete cavities simulation, using a specially developed method[(9)] .

Once these two conditions are fulfilled, the photon counting noise will limit the signal to noise ratio for frequencies above a few hundred hertz.

Index fluctuations

The 3km arms of the interferometer will be kept under vacuum. A fluctuation of residual gas density will create a fluctuation in the light propagation velocity. Being not correlated between the two arms, these velocity fluctuations will produce a fluctuating phase difference between the arms and thus a signal.

The tubes are planned to be kept under a very good vacuum of 10^{-8} mbar in order to ensure the signal to noise ratio not to be limited by this effect.

Laser fluctuations

Due to the small asymmetries between the two arms, a fluctuation in the laser frequency will produce a noise signal. It is therefore important to use a very stable laser. The scheme which will be used in VIRGO is based on the use of a high power laser (20W) which is the slave by injection-locking of an ultra-stable low power (1W) laser. On Fig.2 are shown the results of the R&D which are currently made towards this direction[(10)]. The performance of the frequency stabilisation servosystem is already sufficient to deal with an asymmetry of 1%.

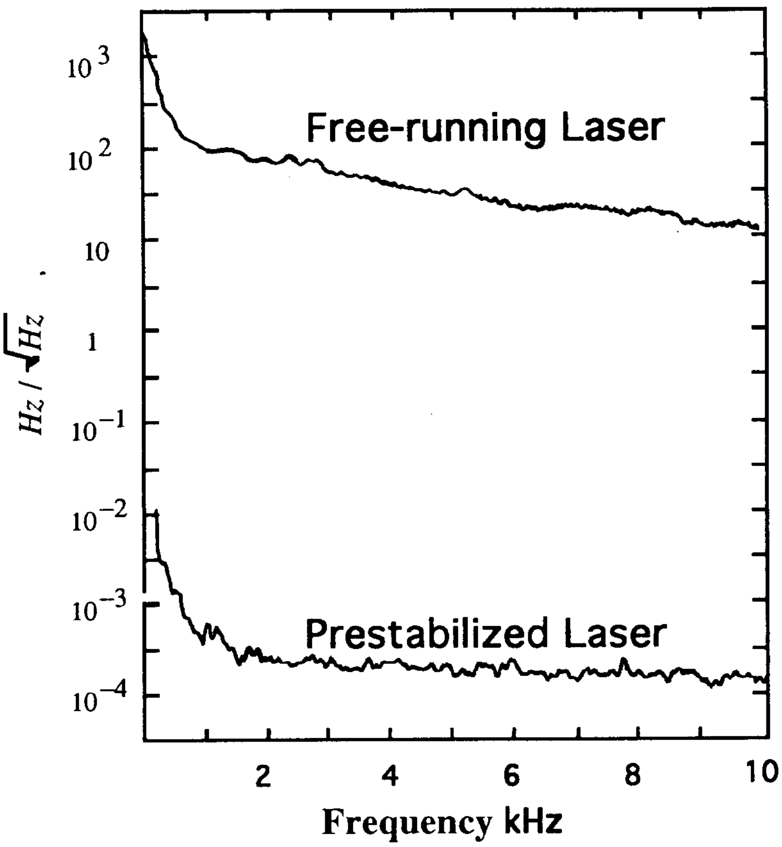

Fig- 2 Frequency stabilization of the input laser

Mirror vibrations

The mirror position fluctuations caused by non gravitational waves effect produce a noise signal, which must be carefully kept at the lowest possible level. In this context, the critical sources of noise are:

1) **the seismic noise** corresponds to the vibrations transmitted via the ground to the mirrors. In order to minimise this effect, the mirrors are suspended at a seven stage blade attenuator. This system is new with respect to the initial proposal in which a gas spring attenuator device was envisaged. The blade springs system produces the same attenuation but is much easier to stabilise. On Fig.3 is shown the global attenuation of this new system. This result is based on measurements performed on a prototype. We see that the seismic noise is very well attenuated down to very low frequencies. At 4 Hz it gives an equivalent sensitivity of $h \approx 10^{-22} / \sqrt{Hz}$, well below the contribution of the thermal noise.

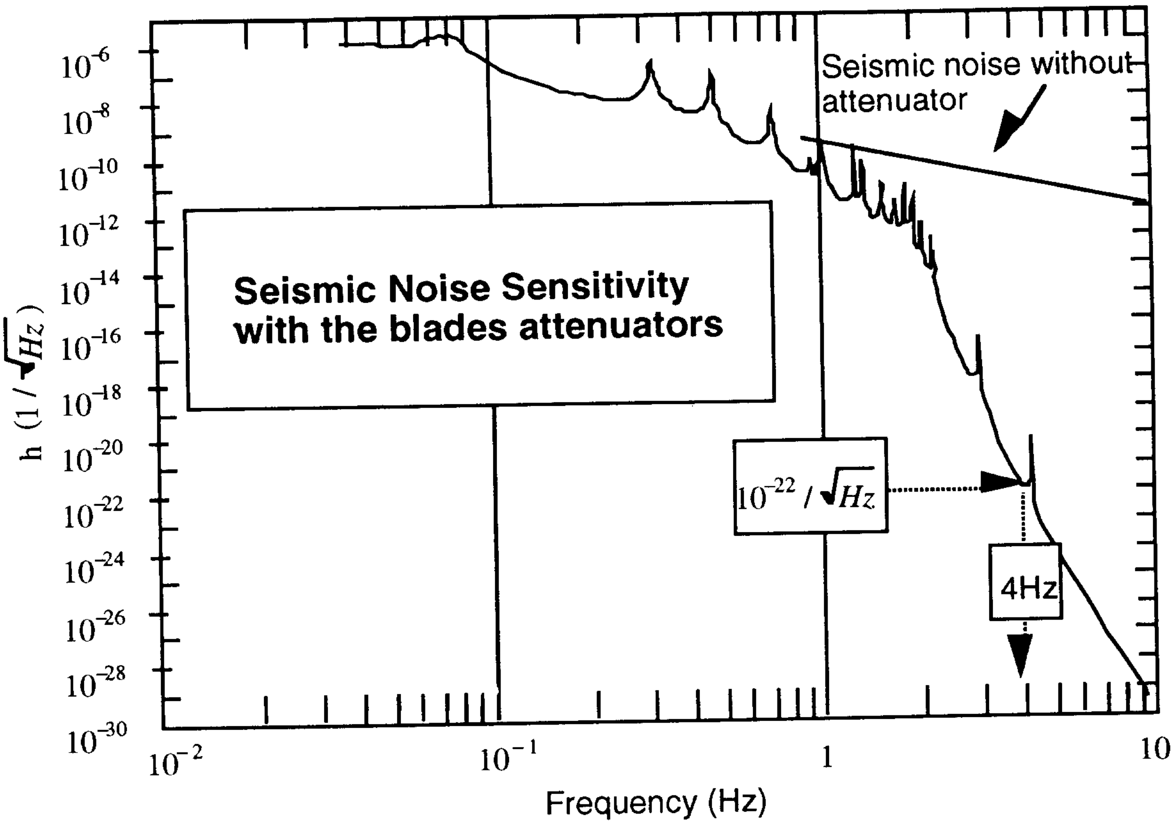

Fig- 3 Seismic attenuation with the blades attenuators

2) **the thermal noise** corresponds to the excitation of the suspension+mirror assembly by the thermal forces. It is the main limitation in sensitivity at frequencies up to a few hundred hertz. The different contributions of these noises are sketched on Fig.4. These calculations are based on the Fluctuation-Dissipation theorem and on its experimental tests(11). An R&D program, both theoretical and experimental, is underway in order to find ways to decrease further this source of noise.

Global sensitivity

On Fig.4 the overall sensitivity is shown. Below 10Hz the graph uses the conservative estimation of the seismic noise contribution and does not take into account the preliminary result obtained on the new super-attenuators which is shown on Fig.3. The dominant limiting effects are thus the seismic noise below 10Hz, the thermal noise of the suspension system and of the mirrors themselves up to about 300Hz. At frequencies greater than 500Hz the dominant source of noise becomes the photon counting noise. The best sensitivity lies in the range 100-200Hz at a value of $h \approx 3.10^{-23} / \sqrt{Hz}$.

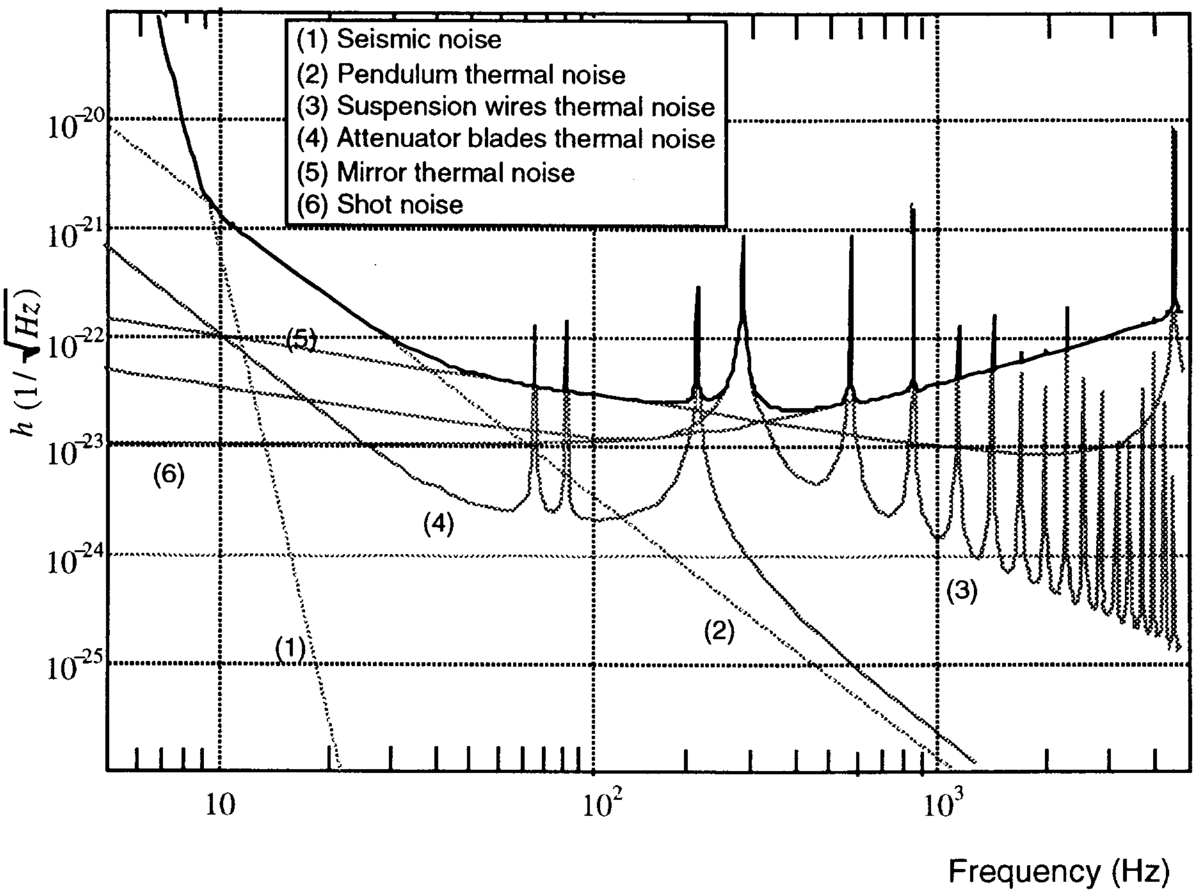

Fig- 4 The VIRGO expected sensitivity

Simulation and Data treatment

Simulation: In order to describe the full behaviour of the VIRGO interferometer, we have developed a simulation program(12) which allows to take into account all sources of noise. This simulation, which is still under development, is an essential tool for the commissioning of the detector and for the running in of data analysis. It helps in finalising parts of the interferometer design, as for instance its global feedback control system.

Data acquisition: The total rate of data to be recorded is expected to be of the order of 600kbytes/s. When recorded continuously over long periods, their amount equals the order of magnitude registered near the large detectors used in high energy physics and calls for a safely organised data management. A Data Acquisition System is being set up(13). It includes a notion of "trigger" on potentially interesting events(14). This triggering scheme is optimised using the above simulation tools.

Data analysis: For all events involving a burst of gravitational radiation, we will analyse the data in coincidences with other similar detectors, like the LIGO project, but also the large arrays of cosmic ray showers detectors, the neutrino detectors and the gamma ray sensitive satellites. The idea behind these coincidences is to find possible correlation between gravitational wave emissions and unexplained phenomena, like the recently observed gamma-ray bursts.

Status of the experiment

The experiment was approved by both the French and Italian authorities in September 1993. This approval includes the funding time-table. The foreseen planning is to start in such a way that we will have a "small interferometer" installed on the final site in 1997, with the final equipment. This "small interferometer" will have the VIRGO specifications except for the quality of the optical components and the length of the arms. This organisation will allow us to test and optimise most of the delicate parts of the experiment (laser, input optics, detection, feed back system) while the optics are realised with their quoted quality (R&D are needed and a special coating machine has to be built for this purpose) and while the 3km vacuum tube is assembled. According to the plans, we expect to take data with nominal sensitivity at the beginning of year 2000.

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