Class. Quantum Grav. **14** (1997) 1461–1469. Printed in the UK PII: S0264-9381(97)81616-4

The Virgo interferometer

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0264-9381/97/061461+09$19.50

Received 6 October 1996, in final form 6 January 1997

Abstract. The Virgo gravitational wave detector is an interferometer with 3 km long arms in construction near Pisa to be commissioned in the year 2000. Virgo has been designed to achieve a strain sensitivity (SNR = 1) of a few times 10^{-23} Hz$^{-1/2}$ at 200 Hz. A large effort has gone into the conception of the mirror suspension system, which is expected to reduce noise to the level of 10^{-21} Hz$^{-1/2}$ at 10 Hz. The expected signals and main sources of noise are briefly discussed; the choices made are illustrated together with the present status of the experiment.

PACS numbers: 0480N, 9555Y

1. Introduction

Measuring gravitational radiation reaching Earth is currently a challenge for experimental ingenuity. In the future it will become a new source of information for astrophysics and cosmology. For this programme to be successful, adequate strain sensitivity over a significant frequency range has to be achieved.

In 1992 a proposal for a large interferometer to detect gravitational waves was submitted to the research funding agencies of France (CNRS) and Italy (INFN). This step followed years of development and prototype testing by groups in Paris and Pisa that demonstrated the feasibility of a wide-band interferometric detector with sensitivity for gravitational waves extending down to 10 Hz.

A collaboration (named after the Virgo cluster) was formed to build a 3 km interferometric detector located in Cascina, near the town of Pisa in Italy [1].

2. Sources accessible to ground-based detectors

Likely astrophysical sources of gravitational radiation can be classified according to the emission duration [2]. Bursts caused by stellar collapse last only milliseconds; inspiralling of tight binary stars can be observed over a time ranging from a few seconds to several hours. With a sensitivity for the strain h of around 10^{-23} events located in the Virgo cluster can be detected with a rate of a few events per year. As a matter of fact today's estimates for rates span two orders of magnitude.

Rotating systems with low dissipation, such as spinning neutron stars or loose binary star systems, emit single-frequency waves over much longer times. In the case of neutron stars the amplitude appears to be too low to be detected by currently planned interferometers, unless suitable averaging of noise is performed.

A stochastic background is predicted to be always present with a continuous frequency spectrum extending, according to the classical big bang model up to a few tens of kHz but with an amplitude out of reach of the present detectors. Recent work on superstrings [3] has rekindled interest in this source by suggesting that the spectrum could extend up to 10^6–10^9 Hz, a region where no astrophysical contribution is expected.

2.1. Coalescence observation and low-frequency sensitivity

Inspiralling binary neutron stars show an increase in radiation frequency ν given by

$$\nu(t) \propto (t_0 - t)^{-3/8} \qquad (1)$$

where t_0 is the time at which coalescence occurs, neglecting higher-order corrections. The amplitude h is related to the wave frequency by

$$h(\nu) \propto \nu^{2/3}. \tag{2}$$

The signal-to-noise ratio in each frequency bin is given by the ratio between $\tilde{h}_{+\times}(\nu)$ and the noise $\tilde{n}(\nu)$ averaged over the time $\mathrm{d}t/\mathrm{d}\nu$ spent in a 1 Hz bin,

$$\frac{\mathrm{d(SNR)}^2}{\mathrm{d}\nu} \propto \tilde{h}^2(\nu)\frac{|\mathrm{d}t/\mathrm{d}\nu|}{\tilde{n}^2(\nu)} \propto \frac{\nu^{-7/3}}{\tilde{n}^2(\nu)}. \tag{3}$$

Even if noise increases, significant gains in SNR are expected by being sensitive at low frequency. If the detection band starts at 100 Hz only the last couple of seconds of life of the binary system can be followed. By being sensitive from 10 Hz such a signal could be registered by the detector for more than 1000 s.

2.2. Low-frequency sensitivity and neutron stars

Rapidly rotating neutron stars are also candidates for emitting gravitational radiation. No precise estimate of the amplitude is available; upper limits are given by attributing the observed decrease in rotation speed to gravitational radiation,

$$h \sim 4 \times 10^{-25} \left(\frac{1\ \mathrm{ms}}{T}\right)^2 \left(\frac{1\ \mathrm{kpc}}{r}\right) \left(\frac{I}{10^{38}\ \mathrm{kg\ m}^2}\right) \left(\frac{\epsilon}{10^{-7}}\right) \tag{4}$$

where T is the rotation period, r the distance, I the moment of inertia and ϵ the ellipticity. The amplitude of the emitted waves is such that only neutron stars in our Galaxy have a significant probability of being detected.

The distribution of rotation speed of a sample of known pulsars [4] peaks around a few Hertz and a substantial tail of observations extends to higher frequencies (millisecond pulsars). No firm conclusions can be drawn about the parent star population from the observed pulsars. However, considering the estimated number of neutron stars in our Galaxy (of the order of 10^9), the pulsar frequency distribution justifies the effort of extending the sensitivity sown to the few Hertz region.

3. Virgo detector structure

The Virgo interferometer measures the distance between detection masses 3 km apart in perpendicular directions.

Limits on the sensitivity in gravitational wave detectors come from a variety of sources [5]; first of all from the residual motion of the masses used. Ground motion is many orders of magnitude larger than the expected signals. Position noise due to thermal fluctuations is the next limitation and is the target of many R&D programmes. A fundamental limit for Earth-based detectors is local gravity fluctuations around the detection masses. Further limitations come from counting photons in the measurement process. To improve the shot-noise limit light is recycled and the circulating power is limited only by the losses in the interferometer.

This results in an apparatus with several mirrors insulated from the ground by a suspension: the four forming the Fabry–Perot cavities, a beamsplitter and a recycling mirror. An injection and a detection bench, together with a mode-cleaning mirror, complete the set-up (figure 1 shows the optical scheme adopted.)

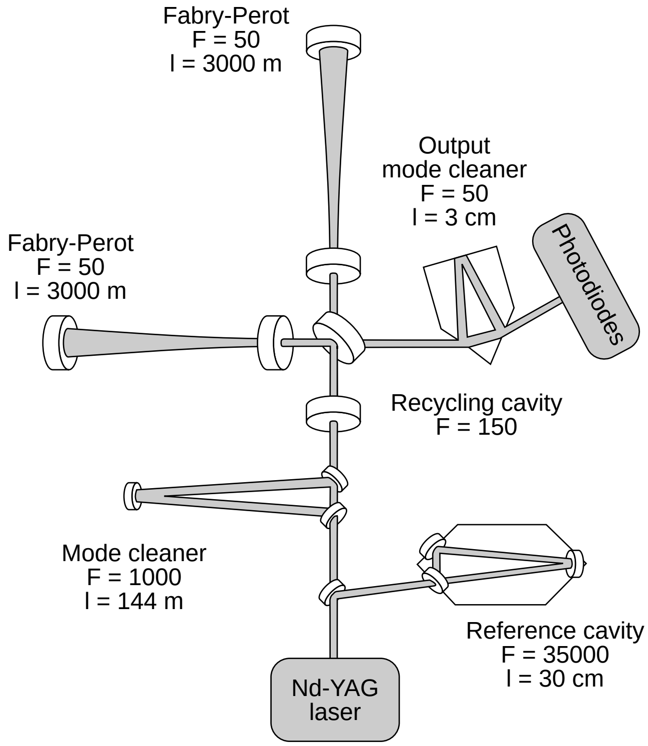

Figure 1. Virgo optical scheme. F is the finesse for the optical cavities. For the recycling cavity this corresponds to a recycling factor of 50. All optics, including the output mode cleaner, are made of silica.

4. The proof mass suspensions

4.1. Seismic isolation

The observed spectrum on the Virgo site in the 1 Hz region is roughly described by

$$\tilde{x}(\nu) = 10^{-6}/\nu^2 \text{ m Hz}^{-1/2} \tag{5}$$

with ν expressed in Hertz. For a 3 km interferometer an attenuation of at least 10 orders of magnitude has to be achieved to detect strains of $\tilde{h} \sim 10^{-21}$ Hz$^{-1/2}$ at 10 Hz.

When one extremity of a spring with a mass at the other end moves, the amplitude of motion of the mass has the well known textbook resonant behaviour as a function of the driving frequency ν. Calling ν_0 the resonance frequency, motion decreases as ν_0^2/ν^2 when $\nu \gg \nu_0$. Following this principle seismic noise filtering is obtained by suspending the detection masses from a cascade of harmonic oscillators. Simplicity of behaviour is obtained by using a pendulum as a harmonic oscillator, with gravity as the loss-free spring. For N identical ideal harmonic oscillators an attenuation

$$A \propto \left(\frac{\nu_0^2}{\nu^2}\right)^N \tag{6}$$

is obtained for frequencies well above the normal mode frequencies of the system. When it comes to building such a system practical sizes result in ν_0 between 100 mHz and 1 Hz.

A compound pendulum designed in Pisa with seven stages each 1 m long and resonant frequencies below 0.5 Hz [6] achieves the required seismic insulation down to 4–5 Hz.

A further stage called the Marionetta, built in Rome, holds and steers the mirror by means of four wires forming another pendulum stage 70 cm long. The Marionetta supports a reference mass that allows the application of a force on the mirror (43 kg) from a quiet support. Figure 2 shows schematically the suspension together with the seven filters, the Marionetta and the mirror. The whole system is kept inside a stiff tower in vacuum.

The present design results in an attenuation from the suspension point to the mirror of $\sim 10^{-10}$ at 4 Hz setting the low-frequency limit for the VIRGO sensitivity due to seismic noise well below 10 Hz.

4.2. Compensation of tides and long-term motion

Ground motion can be of the order of hundreds of microns due to tidal deformation of the Earth's crust and to thermal effects on the surface. Such effects are outside the detection band of Virgo but need to be compensated to meet the stringent requirements on the interferometer working point (for the Fabry–Perot mirrors the RMS fluctuation must be reduced to $6 \times 10^{-6}\lambda$.) The required dynamic range is 10^{14} above the noise floor, well above what a single device can achieve.

Control of the mirror position is achieved in three different places. The fine control that should not introduce any noise is performed from a reference mass suspended on the Marionetta. A rougher control is applied on the Marionetta itself, relying on the filtering characteristics of the last pendulum. Finally, by moving the suspension point the necessary dynamic range is achieved.

The solution adopted for moving the whole suspension (1.2 ton) is to have a support structure that can be deformed (figure 2). A three-leg system with flexible joints at the feet supports the first seismic filter. The low resonant frequency of this inverted pendulum gives an additional attenuation and the noise introduced is only that coming from internal friction of the joints. Rolling systems, which give problems when a clean vacuum is needed, are thus eliminated.

4.3. Thermal noise

The detection masses are in thermal equilibrium with the environment. An average energy of kT is associated with each oscillation degree of freedom, resulting in position fluctuations for the macroscopic coordinates. The frequency spectrum is determined by the dissipation mechanism associated with that motion and can be computed using the fluctuation–dissipation theorem [7] starting from the equation of motion.

Internal friction in materials can be described by adding to the elastic constant of an harmonic oscillator an imaginary term so that the equation of motion reads

$$m\ddot{x} + k(1 + \mathrm{i}\Phi)x = 0. \tag{7}$$

Values for Φ of 10^{-3}, essentially constant over the range of frequency of interest, have been measured in harmonic steel wires. The noise spectrum is different from the case of the viscously damped harmonic oscillator. For $\nu^2 \gg k/m$ the spectrum behaves like $\nu^{-5/2}$ while for $\nu^2 \ll k/m$ a $\nu^{-1/2}$ dependence is obtained.

Virgo assumes that dissipation of the mirror pendulum can be limited to internal friction, allowing a figure of merit of $Q = 10^6$. Recent measurements in Perugia have shown that this target can be reached. Similarly, measurements in Orsay show that $Q = 10^6$ can also be achieved for mirrors.

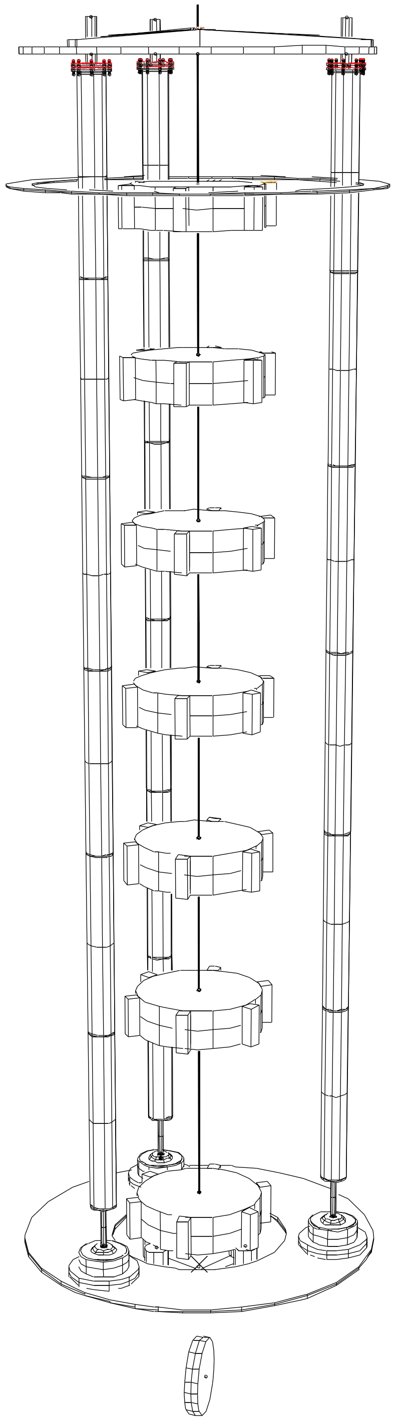

Figure 2. The VIRGO mirror suspension. Distance between filters is 1 m.

5. The interferometer

5.1. Optical scheme

The chosen configuration (figure 1) consists of two perpendicular 3 km Fabry–Perot cavities. Power is recycled by recirculating the light from the beamsplitter. The beam comes from a high-power Nd:YAG laser locked to a stabilized laser. Frequency stability is achieved at low frequencies by locking to a ULE reference cavity conceived by Orsay. Stability at high frequency is achieved by means of the interferometer itself. The beam coming from the laser is filtered by a mode cleaner leaving only the TEM_{00} mode. The signal is filtered by an output mode cleaner to reduce the contributions from diffuse light and spatial modes that have built up in the interferometer.

Alignment of the interferometer is achieved first by local observation by means of CCD cameras and then by use of the Anderson method [8] to extract position and angle error signals from the main beams. Computation and experimentation has been performed by LNF, showing that the method can be applied to the large interferometer.

5.2. Mirror coating and metrology

Coating is performed by making use of dual ion beam sputtering. A coater is being built by IPNL to deal with the large Virgo mirrors. It will also be used to provide corrective coatings. Table 1 shows the results already obtained at IPNL and how these compare with Virgo specifications that are planned to be met for the final interferometer.

Table 1. Progress in coatings at IPNL.

Year	λ (nm)	Absorp. (ppm)	Diff. (ppm)	Wavefront (λ/n)	Mirror ϕ (mm)
1992	633	20	50	n/a	25
1994	633	10	5	n/a	50
	1064	2–3	1–2	n/a	50
1995	633	<0.5	1.2	30	80
	1064	0.5	0.6	n/a	80
Virgo	1064	1	1	100	280

The Virgo mirrors must meet several stringent specifications. As an example simulations show that a 10 ppm absorption in the Fabry–Perot cavities gives a loss of 3% on shot-noise-limited sensitivity; however, a 1 ppm asymmetry in absorptions leads to a 40% loss [9].

At present the mirror coating must be corrected and this process is limited by the precision of measurements. Several instruments have been set up by ESPCI to meet the requirements on mirror metrology.

6. Vacuum system

The entire interferometer must be enclosed in a vacuum chamber with very low residual pressure. Fluctuations in pressure produce changes in the refractive index and so in the actual speed of light. In addition, optics need to be protected from pollutants that could worsen performance in the long term.

The main element is the vacuum tube, with a diameter of 1.2 m. It is equipped with Ti sublimation pumps to achieve a residual pressure of 10^{-9} mbar for H_2. Diffused light effects are reduced by placing baffles inside the tube. Otherwise such light, modulated by tube wall vibrations, would re-enter the beam and introduce an important phase noise.

The tube will be constructed and installed under the supervision of Pisa and Orsay, while LAPP oversees the construction of the towers containing the suspensions and mirrors.

7. Data acquisition and archiving

When Virgo comes into continuous operation large amounts of data (0.5–1 Mbyte s^{-1}) will have to be recorded for off-line analysis. The data acquisition system foresees an on-line fast selection that separately triggers recording of time series containing coalescence or collapse candidates. The data acquisition and recording system is being designed by LAPP, while Naples is creating the archiving system for the data produced and the environment monitoring.

8. Design sensitivity

The expected Virgo performance can be summarized by a sensitivity curve, representing the spectral amplitude of a gravitational wave such that the signal-to-noise ratio is equal to 1 in each 1 Hz frequency bin. Figure 3 shows the sensitivity curve together with the most important contributions for noise. The R&D effort to improve thermal noise of the suspension wires and mirrors and increase the intensity of circulating light are the steps to lowering the detection threshold. It should be noted that a factor of 2 in sensitivity becomes a factor of 8 in observable volume, due to the r^{-1} behaviour of wave propagation.

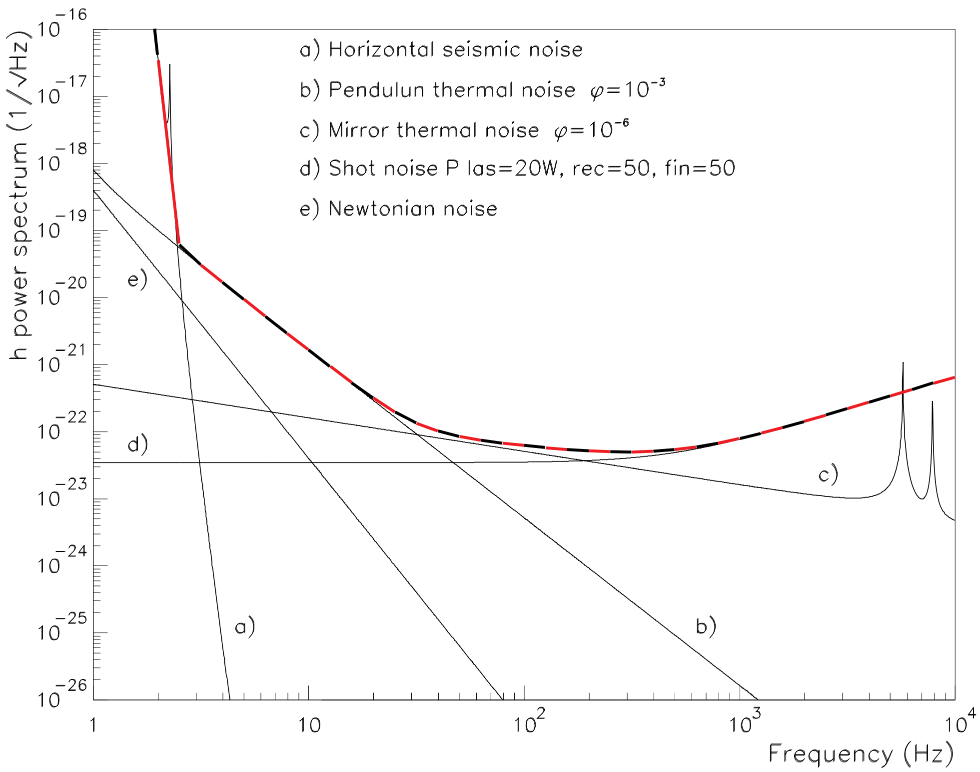

Figure 3. The VIRGO design sensitivity (SNR = 1).

9. Schedule and perspectives

Ground work started in May 1996 after the project was given permission to occupy the necessary land. The construction plan foresees the completion of the central area buildings by mid 1997. An important step will be the commissioning of a Michelson interferometer situated in the central building in 1998 that makes use of the final suspension system. This interferometer will be used to debug and test all the equipment of the central area: laser and injection bench, mode cleaner, detection bench, suspensions and the related control electronics and software. This learning period should provide measurements of several noise terms with adequate sensitivity, allowing for improvements and corrections.

In the mean time arm construction will start together with vacuum tube installation and light is expected to circulate in the full interferometer by mid 2000.

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