Status and perspectives of the Virgo gravitational wave detector

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Abstract

Virgo is the largest gravitational wave detector in Europe. The detector, built by a French-Italian collaboration, is located near Pisa (Italy), and is based on a laser interferometer with 3 km long arms. It aims at the detection of gravitational waves emitted by galactic and extra-galactic sources such as pulsars, supernovae and the coalescences of binary black holes and neutron stars. When operated at its design sensitivity, Virgo should be able to look for gravitational waves in a frequency window comprised between 10 Hz and a few kHz, with a peak strain sensitivity of a few $10^{-23}/\sqrt{Hz}$ around 500 Hz. Since 2003 the detector is going through its commissioning phase. The present status of the experiment and its foreseen upgrades are described in this article.

1. Introduction

Gravitational waves are perturbations of the space-time metric that are generated by any mass having a time-varying quadrupole moment [1]. Similarly to electromagnetic waves, also gravitational waves are transverse, propagates at the speed of light and have two polarization states. Their effect on a set of free falling bodies is to modify their relative distances in a direction perpendicular to the wave vector. Contrary to electromagnetic waves, gravitational waves have a quadrupolar nature; if the distance between two free falling masses decreases along the north-south direction then it increases along the east-west direction, and the opposite will happen half a period later.

Due to the very small value of the gravitational interaction coupling constant the generation of gravitational waves requires a rapidly varying quadrupole moment of compact, massive and relativistic objects. For this reason, gravitational waves of detectable amplitudes are expected to be produced by compact astrophysical sources such as the coalescence of binaries formed by black holes and neutron stars, the collapses of stellar cores or the rotation of non axis-symmetric neutron stars [2]. A background of gravitational waves is expected to be formed immediately after the big-bang. The detection of such a background could provide unique information on the processes taking place at the Planck era.

Among all astrophysical processes, the most promising for ground based gravitational wave detectors are those related to the coalescences of binary black holes or neutron stars. Gravitational waves emitted by binary neutron stars have been indirectly observed measuring the radio-pulses timing emitted by the pulsar in the binary PSR1913+16 [3]. Several systems of this kind have been discovered since then and confirm the observation made with PSR 1913+16. The detection of gravitational waves emitted by compact binaries during the coalescence phase will provide new information on the range of validity of general relativity, the properties of nuclear physics and will be a unique tool for astrophysics and cosmology.

For more than forty years the search for gravitational waves has been pursued with resonant detectors made of a few meters long metallic bars [4]. The development of gravitational wave detectors based on laser interferometers started in the early seventies [5]. After more than two decades of developments the construction of the first interferometers with km long arms started in the nineties. This new generation of detectors [6,7,8] is now entering the operation phase. Virgo [7] is one of the three largest detectors of this kind.

2. The design of the Virgo detector

The Virgo detector is based on a laser interferometer having 3 km long arms. The main features of the detector are shown in Figure 1.Each arm include a Fabry-Perot cavity with a finesse of 50 in order to amplify the phase shift produced by a variation of the arm length [9].

Since one of the limitations to the detector sensitivity is due to the fluctuations of the number of photons detected at the interferometer output port, the sensitivity can be improved by increasing the number of photons injected into the arms thus reducing their relative fluctuation [5]. To this purpose the interferometer output port is tuned to the minimum of transmission so that all the light is reflected toward the laser port. By properly placing an additional mirror (called recycling mirror [9]) between the laser and the interferometer this light is re-injected into the interferometer thus increasing the power impinging on the beam-splitter by about a factor 30 to 40.

The value of the recycling factor depends on the amount of light lost inside the interferometer which itself depends on the quality of the mirror surfaces (flatness and roughness) and on the absorption in the substrates and in the coatings. Keeping these parameters as small as possible becomes more and more difficult as the size of the mirror is increased. The Virgo mirrors are 35 cm in diameter and 10 cm thick, for a total weight of about 20 kg. Special tools for mirror coating and mirror metrology have been developed within Virgo. The final figure obtained for

the mirrors (measured before installation) amounted to 3-4 nm rms for the flatness defects and less than 0.05 nm for the roughness [10].
An alternative way to increase the number of photons injected into the interferometer is to increase the laser power. In practice this possibility is limited by the laser beam quality (geometry and stability) that usually degrades as the power is increased. Moreover a larger power requires that all the associated input optics be able to support the corresponding larger thermal load. The solution adopted by Virgo is a 20 Watt Nd:YVO4 laser, injection locked to a 1 Watt Nd:YAG master laser.
Before the laser beam is injected into the interferometer it is filtered through an first triangular suspended cavity, called input mode-cleaner [11]. This cavity has a finesse of 1000, a length of 150 m and its main purpose is to filter the beam jitter. The same cavity is also used for the laser frequency pre-stabilization. This cavity as well as all the rest of the interferometer is kept under vacuum to eliminate the effect of acoustic noise and of the fluctuations in refraction index.
A shorter mode-cleaner (3.6 cm long) is used at the interferometer output port to filter out the spurious diffused light produced by the mirror defects [12]. As in the case of the input mode-cleaner also this cavity is suspended inside the vacuum system. The beam transmitted by the output mode-cleaner is then detected by InGaAs photodiodes [13] placed outside the vacuum chamber.
All the main interferometer mirrors are suspended to seismic isolators based on six-stages pendulums (shown in Figure 1). Each stage of the pendulum is a seismic filter based on cantilever springs that provide the required vertical isolation [14,16]. The six-stages pendulum is itself suspended to an inverted pendulum that provides attenuation of the horizontal seismic noise starting from 30-40 mHz (depending on the exact tuning) [15]. The total height of the seismic isolator is about 10 m. Attached to the top of the inverted pendulum are three accelerometers [17]. The signals of these inertial sensors properly combined with the signals provided by three position sensors [18] are used to damp the residual motion of the seismic isolator below a few Hz [19].
Each mirror is suspended by means of four thin steel wires (200 μm diameter) to an intermediate mass (called marionette) that is itself suspended to the last stage of the seismic isolator [20]. Also suspended to the marionette is an additional mass, called reference mass, which encompasses the mirror so that its center of mass coincides with that of the mirror. Four coils attached to the reference mass and four small magnets glued to the mirror back face permit to adjust the mirror longitudinal and angular positions. Larger displacements can be obtained by flowing currents through four coils attached to the last stage of the seismic isolator and acting on four magnets attached to the marionette. This ensemble of actuators are used to properly align the mirrors and to control the mirror position in order to keep the interferometer at the required working point. To this purpose a real-time digital control system [21] performs a continuous read-out of the interferometer signals at 20 kHz and acts on the mirror position at 10 kHz.
The design sensitivity of Virgo is shown in Figure 2. Also shown on the same plot are some of the expected signals from potential astrophysical sources. Several uncertainties affect the estimation of the amplitude of gravitational waves emitted by astrophysical sources such as star core collapses and rotating neutron stars. More precise estimates exist in the case of coalescing binary; in this case Virgo will be able to detect signals coming from regions of the universe as far as 30 Mpc thus including the Virgo cluster.

3. Status of Virgo
Virgo has been built by a French-Italian collaboration supported by INFN and CNRS [7].

The construction of the central area (including the central building, the mode-cleaner building and the control building) started in 1996 and was completed in 1998. The central part of the detector was installed and commissioned between 1999 and 2002 using small mirrors [22]. During that period the two arms and the terminals buildings were constructed and the 3 km long vacuum tubes were installed. In the summer of 2003 the last large mirror was installed thus allowing the beginning of the commissioning phase.

3.1 Commissioning of the detector

The commissioning of the interferometer consists of two main parts: the control system set-up and the interferometer noise reduction.

The first includes the set-up and tuning of all the control systems required to maintain the interferometer in the required interference conditions. This was done running the interferometer in optical configurations of increasing complexity. During the very first phase of commissioning a single arm was operated. Then both arms were operated together in the so-called recombined configuration with the power recycling mirror kept misaligned. Finally the whole interferometer was properly aligned and operated. The intermediate steps allowed to test the control systems with simpler optical configurations and to debug interferometer sub-systems separately.

For each of these optical configurations the required interference conditions were obtained progressively. In a first step the so called non-linear automatic alignment is tuned in order to align the mirrors and to properly superpose the axes of the cavities on the incoming beam. This is done using sensors which measure the position of the mirrors with respect to ground to a precision of a fraction of μm and μrad. Once this is done the cavity lengths are locked to a multiple of half-wavelengths to obtain the resonance condition and the interferometer output is tuned to the minimal transmission. To this purpose the laser beam is phase modulated at 6.26 MHz and several error signals are extracted at different interferometer output ports using a synchronous detection technique. The error signals are used to lock the interferometer in a low finesse state. The control system then progressively brings the interferometer output to the minimum of transmission thus increasing the recycling factor to its maximum value [23]. Finally the signals issued by several wave-front sensors based on quadrant photodiodes are used to keep the interferometer at its best alignment. Some of these sensors are in fact already used during the lock acquisition process to increase its robustness.

The second big part of the commissioning work deals with the reduction of the interferometer noise. This work consist in the identification and the reduction of the noise sources limiting the interferometer sensitivity. As the commissioning progresses the interferometer sensitivities is constantly monitored and the noise sources are identified (see Figure 3). In many cases the improvement in sensitivity requires the tuning of some of the control systems. In others it requires to better protect the interferometer from external disturbances acting on those part of the detector that are not suspended under vacuum. In some cases some parts of the electronics need to be revisited or new controls need to be added. This is a relatively long process not easy to plan in detail since many of the noise sources couple with the interferometer output through small imperfections of the interferometer that are difficult to predict a priori.

One of the main difficulty found at the beginning of the commissioning was due to the light reflected by the interferometer toward the input mode-cleaner and then back scattered by the latter toward the interferometer. This produced spurious interference fringes which made the interferometer locking impossible. The problem was temporary solved by introducing an optical attenuator between the input mode-cleaner and the recycling mirror at the price of reducing the power injected into the interferometer by one order of magnitude, but allowing the first lock of the interferometer. Later this problem was eliminated by a complete redesign of the input optics including a large Faraday isolator placed under vacuum. This permitted to increase the power injected into the interferometer from 0.7 W to about 7 W in 2006. As the power was increased new difficulties appeared due to the mirrors thermal deformation. This required to slightly reduce the power and to re-visit the lock acquisition process to deal with the thermal transient. The lock acquisition process that required a few minutes at low power now lasts for about 20 minutes. A mirror thermal compensation system, currently under development, should allow to reduce this problem.

Several data taking periods have been performed during the commissioning phase. The sensitivity measured during these periods is shown in Figure 4. During data takings C5-C7 the interferometer was operated in the recycled configuration at low power while during WSR1 and WSR6 the interferometer was operated at high power. The best sensitivity measured so far is about a factor of three lower than the design value above 1 kHz and one to three orders of magnitudes at lower frequencies. The maximum distance at which a coalescing binary formed by two neutron stars would be detectable is 3 Mpc that is a factor of ten from the design sensitivity. The present sensitivity is limited by shot noise above 1 kHz and by a combination of control noises below 150 Hz. At intermediate frequencies some currently investigated diffused light phenomena make the interferometer sensitive to acoustic noise.

Since September 2006 a soft transition from commissioning to data taking has started. Whenever compatible with the on-going commissioning activities data are collected during the weekends. A first long data taking lasting several months is expected to take place in 2007 at the end of this transition period.

3.2 Data analysis preparation

The setting up of the data analysis pipelines has started several years ago. The detector produces about 6 to 8 MB/s of compressed data that, integrated over one year correspond to about 200 to 250 TB of data. This explains the need of having all the data analysis pipelines well in place before the long data taking is started.

The data analysis preparation consists of several activities. The main core of the work consists in the development and test of search algorithms for each class of sources. The algorithms are tested on real data using either hardware injections i.e. fake gravitational wave like signals injected in the interferometer using the coils-magnets actuators or software injection i.e. fake signals added to the data once they have been collected. Before the algorithms could run on the data the interferometer output needs to be calibrated and the strain signal reconstructed. This is done by measuring the frequency response of the interferometer and monitoring the evolution of this calibration curve as a function of time.

Another important part of the work consists in the development of vetoes to reduce the false alarm rate. Different kind of vetoes are used: epoch vetoes based on the state of the interferometer are applied a-priori before the algorithms are run on the data while a-posteriori vetoes that use the output of the search algorithms are instead applied at the end of the process. Finally vetoes are developed using auxiliary channels that monitors the various interferometer sub-systems, the interferometer control systems as well as the environmental noise. About 1500 auxiliary channels are available for this purpose.

This preparation of the data analysis pipelines have been considerably accelerated as the commissioning of the interferometer started and real technical data became available. One of the main difficulties encountered when analyzing real data has been the need to deal with the non stationarity of the interferometer noise.

Since the earth is transparent to gravitational waves, these are expected to produce similar signals on all detectors on earth, the differences being due to the detector orientations and to the time delay related to the distance between the detectors. The observation of coincident signals at the output of several widely spaced detectors is considered to be the most important

method to distinguish between a fake effect and the detection of a gravitational wave. Moreover the coincident observation in at least three detectors is a necessary condition to reconstruct the source location. For this reason the exchange of data and their analysis in coincidence is a usual practice in this field and all the experiments are using the same data format.
In this context the Virgo collaboration is preparing the analysis of the data in coincidence with the LIGO interferometers since a couple of years. The first step has been the joint analysis of simulated data produced by the Virgo and LSC collaborations. These studies have shown that adding Virgo to the LIGO network permits to increase the detection efficiency by 30% to 50% depending on the kind of source [24,25]. The next step , currently in progress, will consist in repeating this work using a few hours of real data. In parallel with this preparatory work an MOU is being signed between VIRGO and LIGO. The agreement foresees full data exchange, joint data analysis and joint publications.

4 Virgo+ and Advanced Virgo

The Virgo design sensitivity will allow to test some of the present gravitational wave amplitude upper limits. Even if a first detection is possible, the sensitivity of Virgo and LIGO will not be sufficient to open the era of the gravitational wave astronomy. For this reason it is important to prepare the upgrades of the present detector [26], considering that an increase of the sensitivity by only a factor of 2 will increase the expected event rate by about 2^3.
Thanks to the seismic isolators, seismic noise is expected to be negligible above a few Hz and the Virgo design sensitivity (Fig. 5) is limited by thermal noise from 10 Hz to a few hundreds hertz. At higher frequency the limitation comes from photon shot noise. As a consequence it is possible to improve the Virgo sensitivity with a set of medium scale incremental improvements, keeping the seismic isolation and the optical lay-out unchanged.
The sensitivity at high frequency will be improved by adding a laser amplifier behind the present laser system thus increasing the injected power from 10 W to 25 W. In order to cope with the already observed mirrors thermal deformation, a thermal compensation system able to compensate for the increase of laser power will have to be installed.
At lower frequencies the sensitivity will be improved by changing the present steel wires for the mirror suspension with the so-called monolithic suspensions, where fused silica fibers soldered to the mirrors are used to suspend the mirror to the marionette. At the same time the present Fabry-Perot cavity end mirrors made of Herasil silica will be replaced with less lossy Suprasil mirrors thus improving the internal thermal noise of these test masses.
In order to take full advantage of these two improvements the control system electronics will also be upgraded in order to reduce the sensitivity to electro-magnetic disturbances, to increase the system capabilities and to eliminate obsolete components.
The planned new sensitivity is shown in Figure 5. The maximum distance at which a coalescing binary is expected to be detectable is about 110-150 Mpc for a binary formed by neutron stars and about 550-750 Mpc for a binary of black holes.
This ensemble of upgrades, known as Virgo+ [26], is expected to be implemented in 2008. The procurement of the laser and of the new mirrors was started in 2005 and the first monolithic suspension is being assembled at the site.
A more substantial upgrade, called Advanced Virgo, will take place at the beginning of the next decade. In this case the goal is to improve the sensitivity by one order of magnitude (with respect to Virgo) thus increasing the event rate by about three orders of magnitude.
In this case several areas of improvement are expected [27]. The injected power will be further increased. The possibility to have a fully fibered injection system is being investigated. Monolithic suspensions will be re-visited to consider electro-static actuators as well as more stringent cleanliness requirements. Larger mirrors will very likely be used with, possibly ,

lower loss coatings in order to reduce the effect of radiation pressure noise and thermal noise. Finally the optical configuration will be upgraded in order to use larger beam diameters on the cavity input mirrors and, probably, signal recycling techniques.
The conceptual design of Advanced Virgo is expected to become available by the end of 2007. An R&D program, devoted to the preparation of Advanced Virgo, will start in 2007 with the goal to be able to start the engineering phase in 2009.

5. Conclusions

The commissioning of Virgo with 7 W of injected laser power started in 2006. During the last data taking the detector sensitivity expressed in terms of the maximum distance at which a coalescing binary formed by two neutron stars would be detectable attained 3 Mpc i.e. a factor of ten from the design sensitivity. A first long data taking will be performed in 2007 and will be followed by a set of medium scale upgrades called Virgo+. A joint VIRGO-LIGO data analysis program has started and will be formalized soon. During the next few years Virgo will participate to the world-wide search for gravitational waves. The on-going and forthcoming R&D allows to plan a substantial upgrade of the present detectors that during the next decade will extend the search for gravitational waves to distances in the 100 Mpc to 1 Gpc range.

References

[1] Misner C. W., Thorne K. S., Wheeler J.; Gravitation, Freeman W. H., S. Francisco (1973)
[2] Thorne K.S.; Gravitational Radiation in: 300 Years of Gravitation, Cambridge University Press, Cambridge (1987)
[3] Weisberg J.M. e Taylor J.H.; Physical Review Letters 52 1348 (1984)
[4] TBD
[5] R. Weiss, Quarterly Progress Report of the Research Laboratory of Electronics, MIT 105 (1972) 379
[6] http://www.ligo.caltech.edu
[7] http://www.virgo.infn.it
[8] http://geo600.uni-hannover.de
[9] R.W.P. Drever in: Gravitational Radiation, Proc. Les Houches Summer Institute, eds. T.Piran and N.Deruelle (North-Holland, Amsterdam, 1982) p.321
[10] F.Beauville et al.; Class. Quant. Grav. 21 (2004) S935-45
[11] F. Bondu et al., Class. Quant. Grav. 19 (2002) 1829
[12] F. Beauville et al., Class. Quant. Grav. 23 (2006) 3235-3250
[13] R. Flaminio, Nucl. Instr. and Meth. A 409 (1998) 477
[14] G. Ballardin et al., Rev. Sci. Instrum. 72 (2001) 3643
[15] G. Losurdo et al., Rev. Sci . Instrum. 70 (1999) 2507
[16] S. Braccini et al., Rev. Sci. Instrum. 67 (1996) 2899
[17] S. Braccini et al. ; Rev. Sci. Instrum. 66 (1995) 2672
[18] H. Tariq et al., Nucl. Instr. and Meth. A 489 (2002) 570
[19] G. Losurdo et al., Rev. Sci. Instrum 72 (2001) 3653
[20] A. Bernardini et al., Rev. Sci. Instrum. 70 (1999) 3463
[21] F. Cavalier, 'Le contrôle global de Virgo' Thèse d'habilitation à diriger des recherches, Université Paris Sud, LAL 01-69 (2001)
[22] F. Acernese et al., Astroparticle Phys. 21 (2004) 1
[23] F. Acernese et al, Class. Quant. Grav. 23 (2006) S85
[24] F. Beauville et al., Class. Quant. Grav. 22 (2005) S1293
[25] F. Beauville et al., Class. Quant. Grav 22 (2005) S1149
[26] R.Flaminio et al., 'Advanced Virgo White Paper', VIR-NOT-DIR-1390-304
[27] Virgo Collaboration, 'Guidelines for Advanced Virgo R&D' VIR-NOT-DIR-1390-325

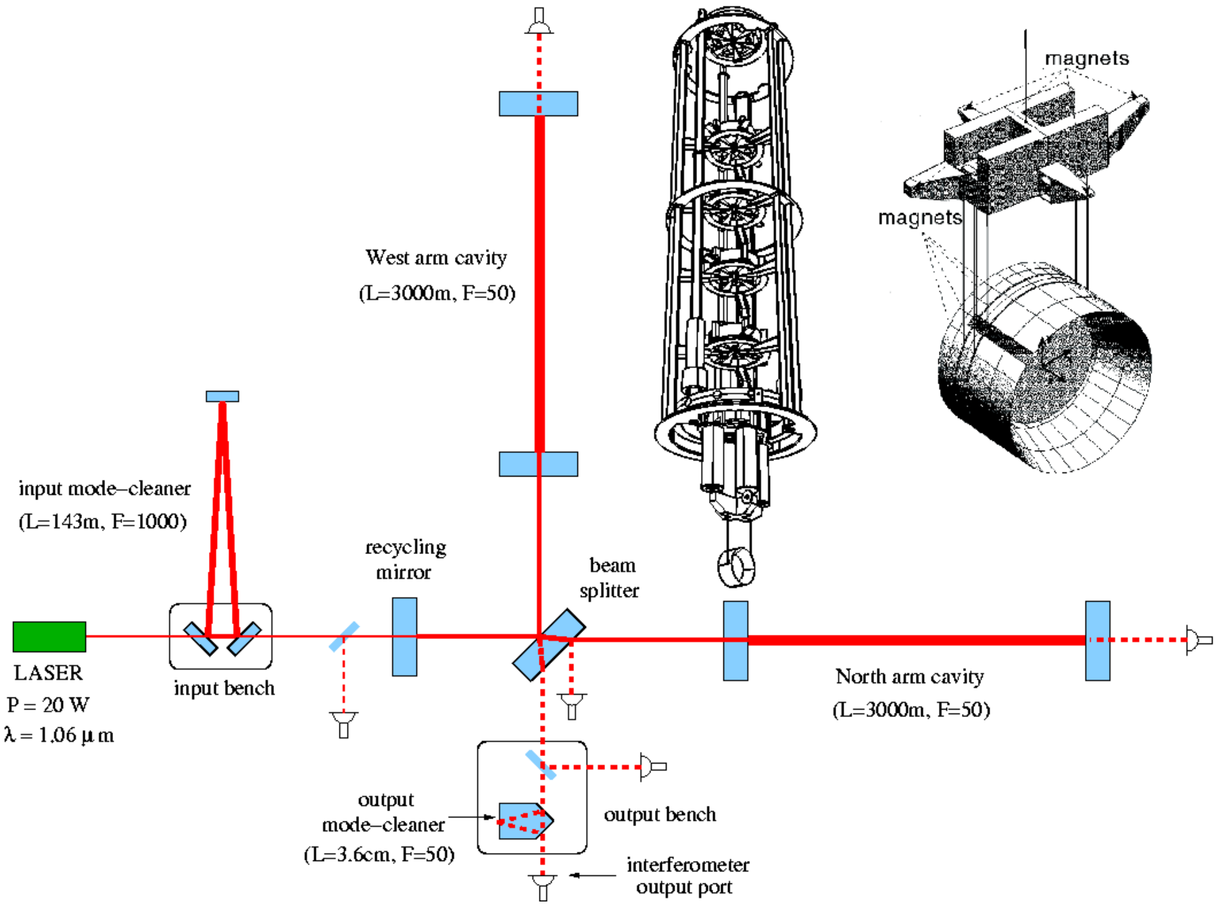

Figure 1. The optical lay out of the Virgo interferometer. Also shown is a 3-D view of the seismic isolator to which each mirror is suspended.

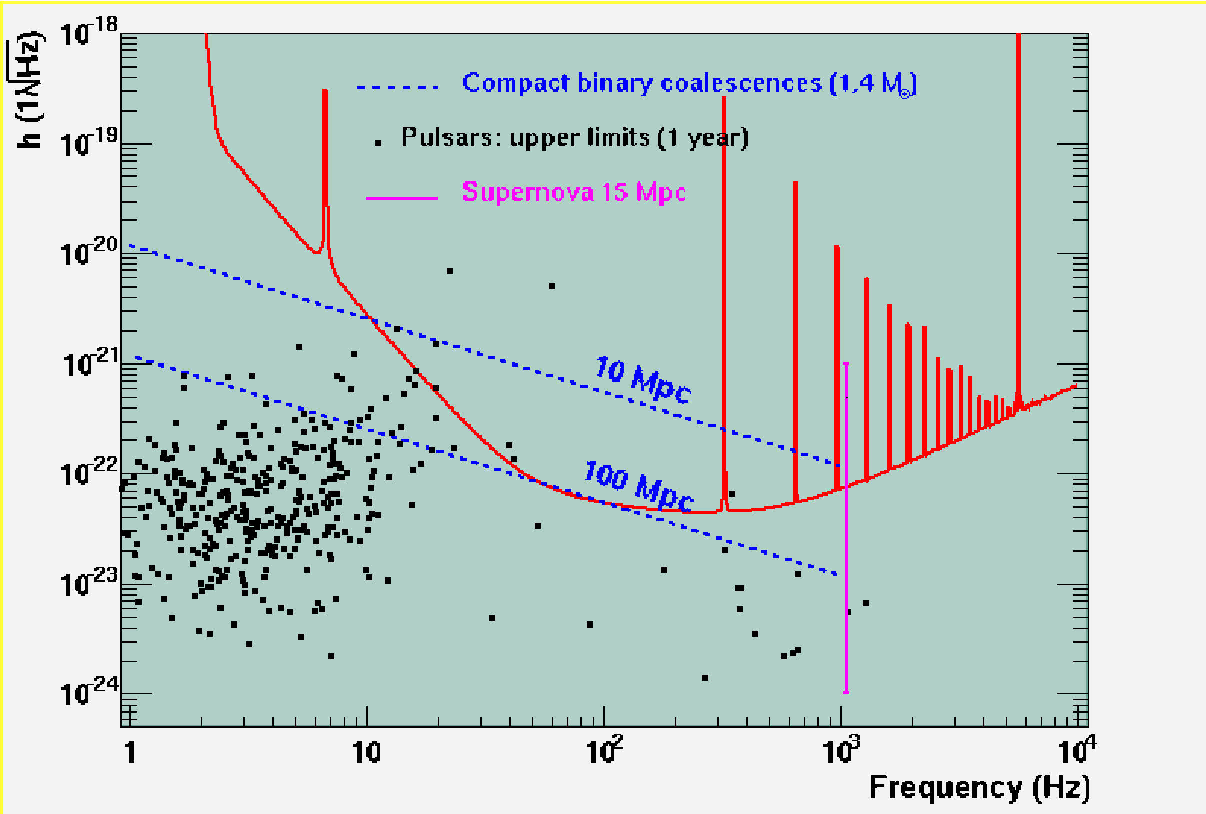

Figure 2. The Virgo design strain sensitivity as a function of the frequency. For comparison the amplitude of some of the expected sources are superposed on the same plot.

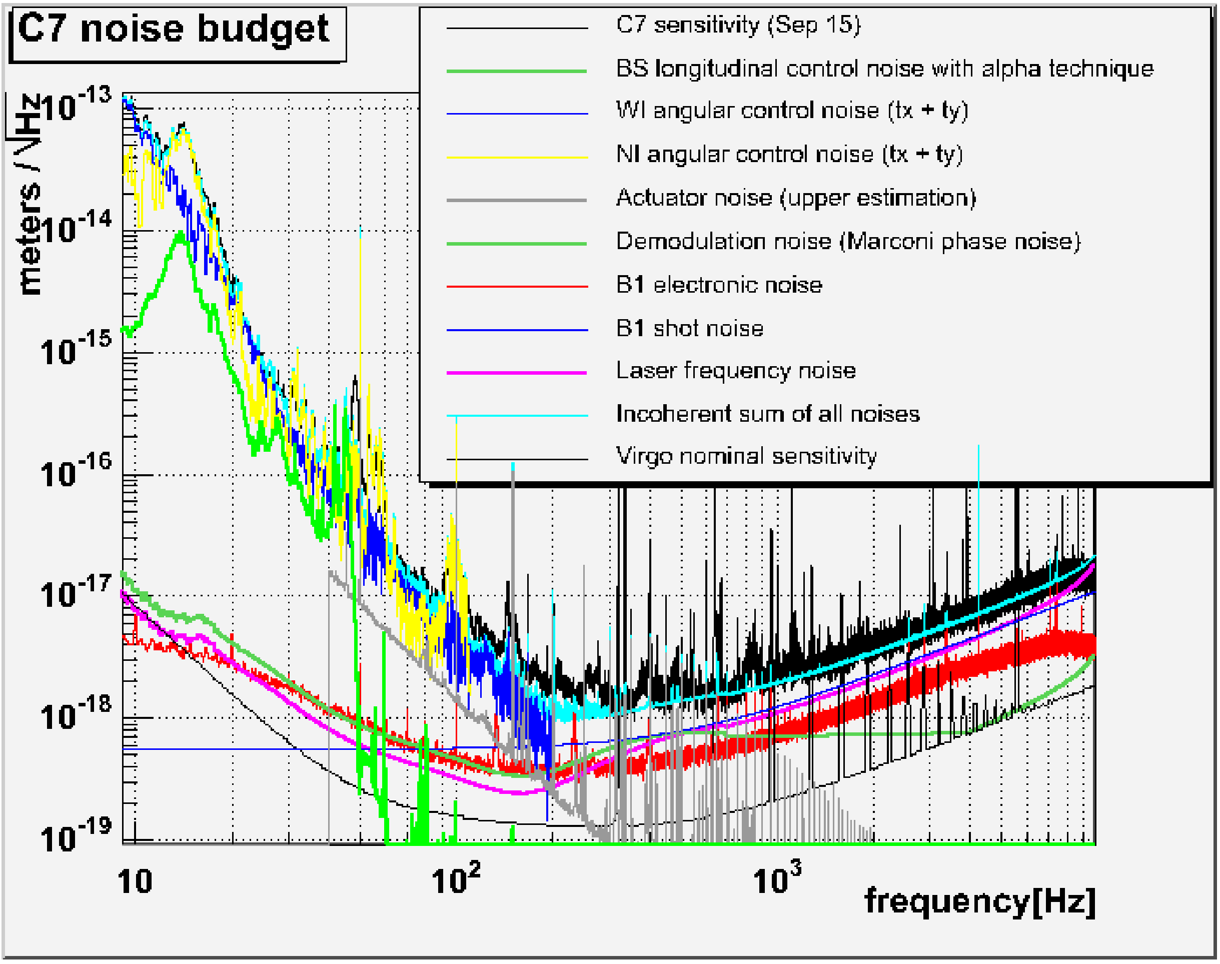

Figure 3. The Virgo interferometer displacement sensitivity measured during the C7 run is shown together with the identified noise sources.

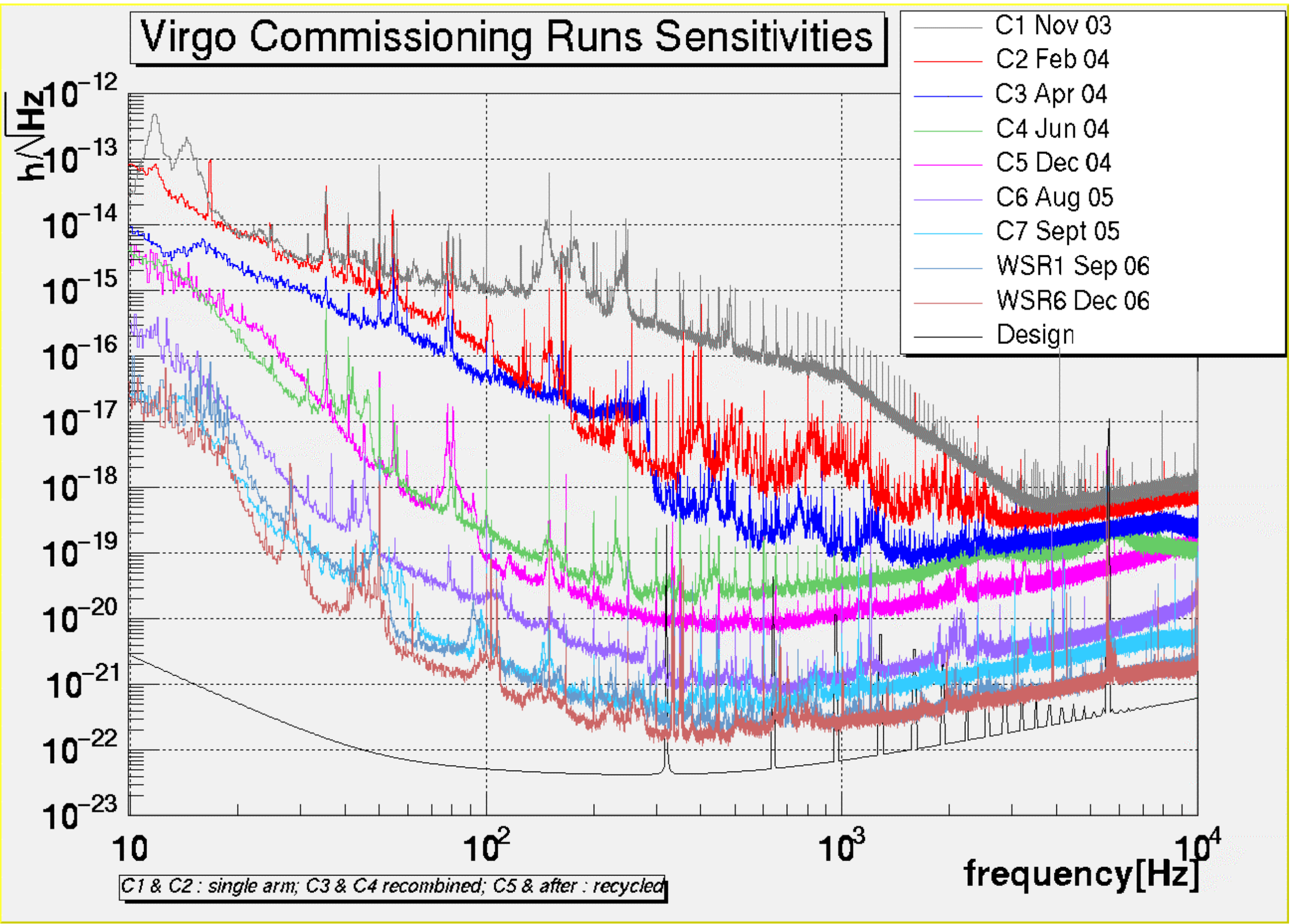

Figure 4. The Virgo interferometer sensitivity measured during the data takings performed since the commissioning phase started in 2003.

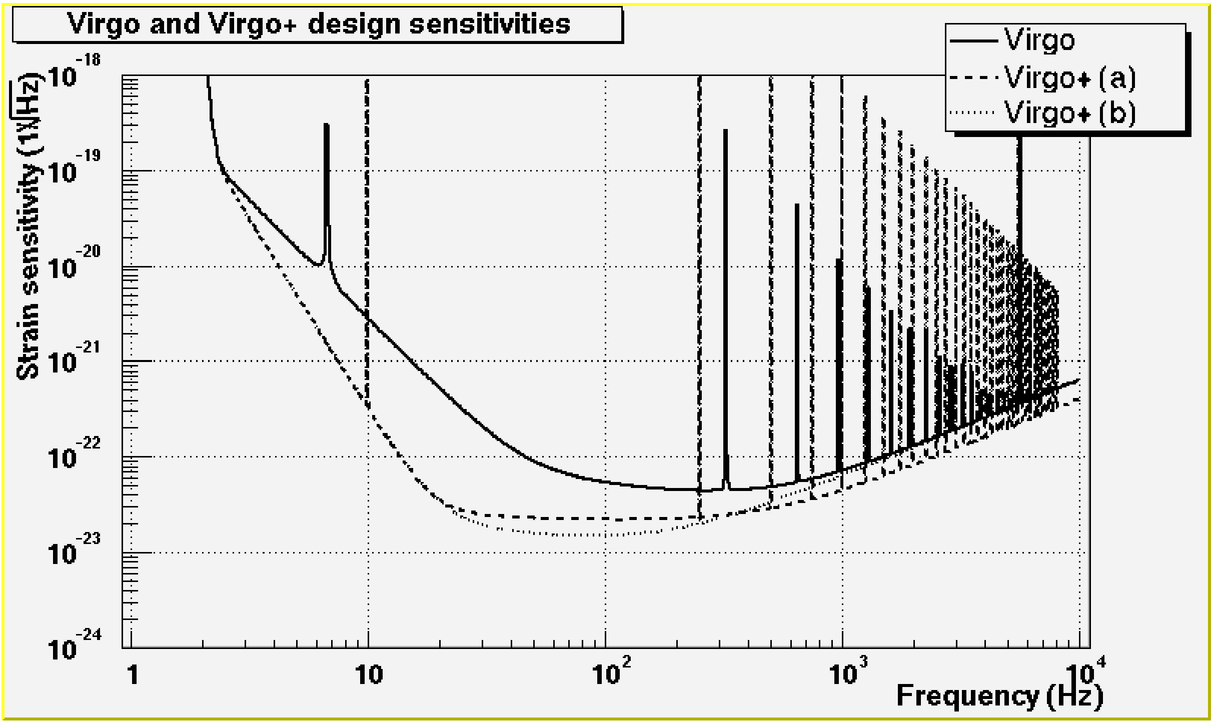

Figure 5. The Virgo design sensitivity (plain bold curve) compared to two possible Virgo+ sensitivities differing from the choice of the cavity finesse. It is assumed that control noise can be reduced below fundamental noises (thermal and shot).