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The Status of Virgo

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Abstract: The commissioning phase of the full *Virgo* gravity-wave interferometric detector started in September 2003, and is still progressing. This activity is intended to achieve a stable operation of the detector, at its design strain sensitivity, in the frequency bandwidth extending from about 10 Hz up to a few kHz, with a value of a few 10^{-23} around 500 Hz.

In October 2004 the interferometer was locked for the first time in *recycled* configuration, with the laser power reduced by a factor of 10. In April 2006, after some important modifications of the input optics, the commissioning was able to continue with the full beam power restored. This new phase was also characterized by a strong boost to the noise hunting activity. From September 2006, at the time of this conference, monthly weekend science run (WSR) were planned to test the detector performance and reliability, and to prepare the transition to the long scientific data taking period which is foreseen for 2007.

Even if Virgo has not yet achieved a good enough sensitivity for the scientific detection of real events a great deal of work has been carried out to set-up the analysis pipelines and the veto algorithms. The partnership with other gravity-wave detectors has progressed, and a *Memorandum of Understanding* for a closer collaboration with LIGO is being signed in 2007.

Also the plans of future development, in order to improve the Virgo sensitivity, are substantially defined and foresees actions to be performed in various times.

In this article the main features of Virgo, together with its actual status and the plans for its future upgrade, are presented.

Figure 1: Aerial view of the Virgo detector

1 Introduction

The *Virgo* gravitational wave detector (see figure 1) is a long baseline *recycled Michelson interferometer*, with 3 km long *Fabry-Perot* cavities in its arms [1]. It was designed and built by a French-Italian collaboration constituted by CNRS (France) and INFN (Italy). Virgo is located within the *European Gravitational Observatory* (EGO) [2], near Pisa (Italy). Its mission is to detect gravitational waves from astrophysical sources up to the distance of the Virgo cluster, being able to sense displacements of its mirror test masses by less than 10^{-18}m, in a frequency bandwidth extending from a few kHz down to about 10 Hz [3].

Conceptually Virgo shares the same detection principle of other gravity-wave detectors in the world: such as LIGO [4], TAMA [5] and GEO [6]. Gravitational waves, when impinging upon the interferometer, drive the change of the relative length between free falling mirrors. The induced phase difference, between the two arm beams, is directly measured in the interferometer signal at the output port.

The commissioning phase of the full Virgo started in September 2003 and is still progressing towards the objective of a stable operation at the design sensitivity.

In the following sections the main design features of the detector, its actual status and future perspectives, are presented.

2 The Virgo detector

A simplified representation of the optical layout of Virgo is shown in figure 2. It reproduces the scheme of a recycled Michelson interferometer, with 3km long Fabry-Perot cavities having a finesse of about 50 (*north* and *west*-cavity). The *recycling cavity* is constituted by the input *Power Recycling* (PR) mirror and the rest of the interferometer.

The large main mirrors (with a mass of 10-20 kg) are high-quality fused silica pieces with very low absorption and scattering, and are kept in vacuum, to reduce phase fluctuations produced by the beam couplings with acoustic and refraction index noises. The level of the vacuum partial pressures are of the order of 10^{-9} mbar for H_2 and 10^{-13} mbar for hydrocarbons. The Virgo vacuum system has a remarkable volume of about 7000 m^3 [7].

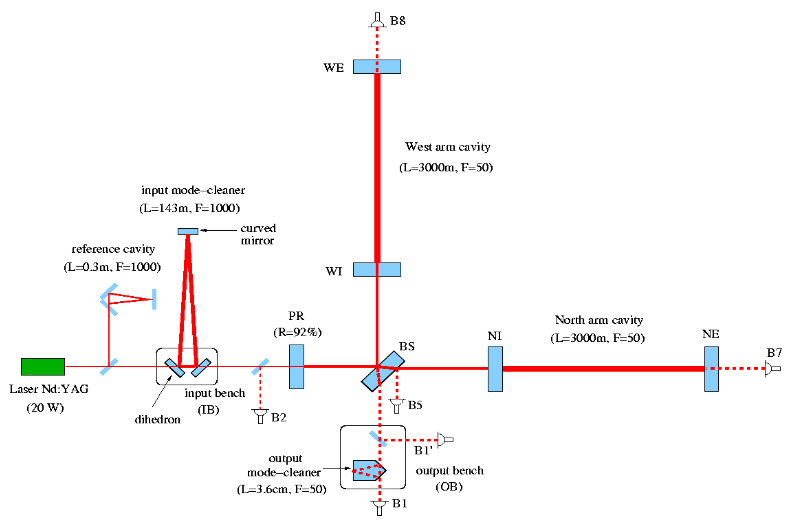

Figure 2: The Virgo interferometer optical layout

By design a laser beam of 20 W power, and a wavelength of 1064 nm, is provided by a *Nd:YVO4* high power injection laser, locked to a 1 W *Nd:YAG* master laser.

Before entering the interferometer the beam jitter is filtered by the *Input Mode Cleaner* (IMC) [8]: a triangular cavity, having a length of about 143 m and a finesse of 1000. The IMC is also used as reference to pre-stabilize the laser frequency. For its part, the length of the IMC is stabilized against the low frequency variations, below 15 Hz, using as reference a 30 cm long *reference cavity*, made of *ULE*, a very low thermal expansion material.

After the IMC the beam is injected into the interferometer, through the PR mirror, with about 10 W of available power. After the PR mirror the light is splitted by a 50% *Beam Splitter* (BS) mirror, and the two resulting beams are injected into the Fabry-Perot cavities. Each of the two beams, resonating into these cavities, can be seen as traveling along an equivalent optical path of about 100 km; thus their relative phase difference is amplified.

At the output port of the interferometer, another 36 mm long mode-cleaner, denominated *Output Mode Cleaner* (OMC) [9], filters the spurious diffused light produced by the mirror defects. After the OMC the interferometer signal is detected by *InGaAs* photodiodes placed outside the vacuum chamber.

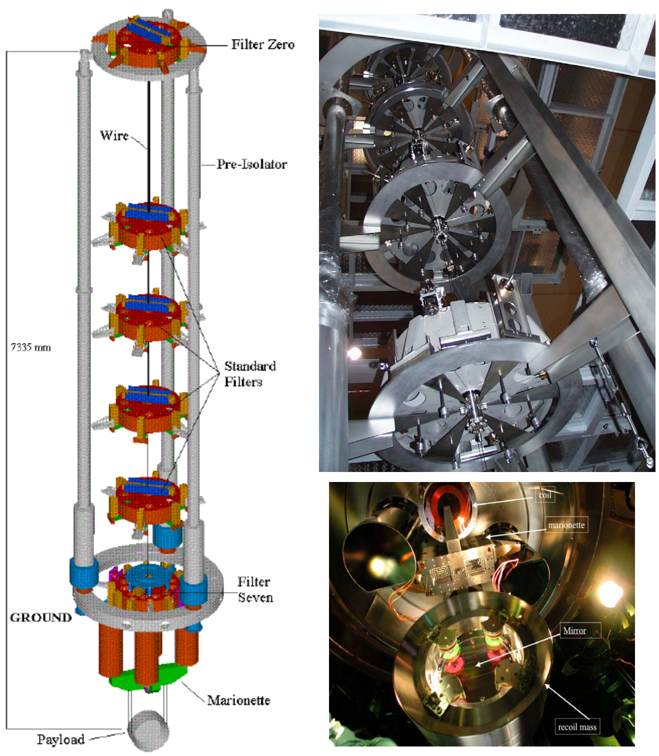

Figure3: The Virgo Superattenuator (SA)

The accuracy of the optical read-out is limited by the *shot noise* fluctuations of the number of detected photons. This counting noise scales as $\sqrt{P}$, where P is the power circulating into the interferometer. To enhance the interferometer sensitivity the arms length are tuned to keep the output port on the *dark fringe*. In this configuration almost all the light is reflected back to the input port and is stored into the recycling cavity, thus enhancing the power impinging upon the BS mirror by about a factor of 40.

In all ground based detectors *seismic noise* is an important sensitivity limiting factor: at 10 Hz the typical level of ground vibrations is about 10^{12} times larger than any expected gravitational wave signal. In order to extend the detection frequency bandwidth, down to about 10 Hz, the Virgo interferometer mirrors are suspended to a complex low frequency seismic vibration isolator (see figure 3) called *Superattenuator* SA [10][11]. Based on the principle of the passive mechanical low-pass filtering action of a multi-stage harmonic oscillator, the 8 m high SA performs like a six-stage pendulum. At frequencies higher than the SA main resonances, above 10 Hz, the mirrors behave as free falling test masses. The first five stages are also equipped with a set of triangular *maraging steel* cantilever springs, providing the isolation along the vertical direction. The top-stage of the multiple pendulum consists of another mechanical filter, called *Filter Zero*, that provides vertical attenuation. The Filter Zero is clamped to a surrounding steel ring connecting the three, 6m long, aluminum legs of a so called *Inverted Pendulum* (IP). The IP acts as a pre-isolator stage along the horizontal direction, with a cut-off frequency of about 40 mHz [12]. The amplitude of the SA resonant motions, below a few Hz, are limited by an active control loop, denominated *Inertial Damping*: the rms residual motion is reduced by a factor 100, down to less than 0.1 μm [13]. The feedback error signal is given by an appropriate combination of a set of three accelerometers [14] and three LVDT (Linear Variable Voltage Transducer) displacement sensors [15], mounted on the top of the IP. The feedback force is exerted by a set of three coils, connected to ground, acting on magnets also placed on the top of the IP.

The last stage of the SA, historically denominated *Filter 7*, supports an intermediate steering element called *Marionette* [16]. Each mirror is suspended to the Marionette by means of four thin steel wires, with an effective pendulum length of 0.7 m. The Marionette was designed to steer and control the mirror along its longitudinal and angular degrees of freedom. The necessary forces and torques are provided by two couples of longitudinal and vertical coils, mounted on the Filter 7, acting on magnets mounted on the four arms of the Marionette. The fine control of the mirror along the beam is achieved by four horizontal coils acting on magnets glued on the back of the mirror. These coils are supported by the so called *Reference Mass*: a cylinder shaped element that is independently suspended to the Marionette encompassing the mirror with coinciding centers of mass, in order to recoil against each other without inducing displacements of the other elements of the chain.

The seismic noise attenuation of the SA has been deeply tested after its installation on the detector. Measurements performed using the signal from the interferometer have confirmed an attenuation, at the mirror level, of about 14 orders of magnitude at 10 Hz [17].

To maintain the interferometer *locked*, with the beam resonating in the Fabry-Perot and recycling cavities and the output port tuned on the dark fringe, mirrors are required to deviate from their working point by less then 10^{-12} m rms. The locking conditions are held by an active feedback control. The mirror are previously kept around their working point, with an accuracy of about 1μm rms, by a *Local Control* system [18] referred to ground, which act on the bottom part of each SA. The relative displacements of the mirrors are detected by a carrier beam phase modulated at 6.26 MHz, using the standard *Pound-Drever-Hall technique* [19] [20]. The signals from photodiodes placed at different interferometer output ports, are synchronously demodulated and mixed to reconstruct all the relevant lengths. Then these error signals are digitized and sent via optical links to the *Global Control* [21], a real time computing system that send, at a rate of 10 kHz, the correction signals to the mirror suspension actuators.

The design sensitivity of Virgo interferometer, expressed in terms of the dimensionless relative deformation (*strain*) of the arm length, is shown in figure 4.

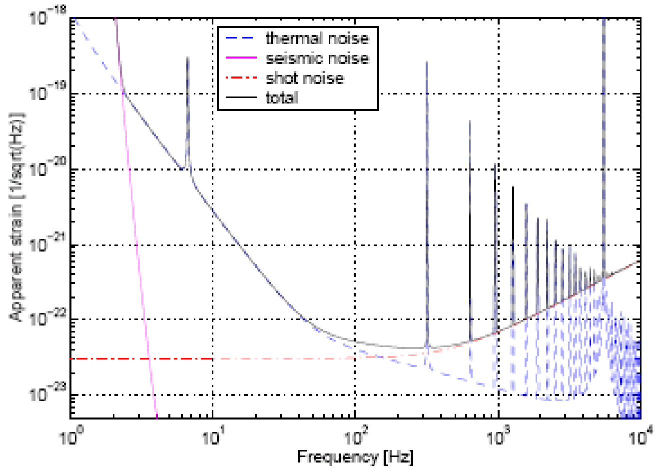

Figure 4. The Virgo design strain sensitivity

Thanks to the SA suspension system the sensitivity is limited by seismic noise only in the low frequency region below 4 Hz. Thermal noise, associated with the Brownian motion of the mirror pendulum is dominant in the frequency bandwidth between 4 Hz and 100 Hz; while the mirrors substrate and coating thermal noise affect the sensitivity in the region between 50 Hz and 500 Hz. The shot noise limitation becomes evident at frequencies higher than 500 Hz. The amplitude of the design strain sensitivity is of a few $10^{-21}\sqrt{Hz}$ at 10 Hz, and a few $10^{-23}\sqrt{Hz}$ in the region around 500 Hz.

3 Commissioning and status of Virgo

During the period between 1999 and 2002, while the work on the two long arm vacuum pipes and terminal towers buildings was still progressing, the central part of the Virgo detector, a recycled Michelson interferometer with smaller mirrors (CITF), was installed and commissioned. A great deal of experience was gathered in integrating the various subsystems, and in approaching all the novel arising issues. The controllability and feasibility of the interferometer components and its complex suspension system was satisfactorily demonstrated [22][23].

The commissioning of the full Virgo detector started in September 2003, after the completion of its installation, and advanced in a gradual manner, investigating step by step the set-up of the various sub-system active controls, along with optical configurations of growing complexity.

First each Fabry-Perot cavity was aligned and locked at the resonance. In February 2004, the interferometer was locked in the *recombined* configuration: with both the Fabry-Perot resonating, and the power recycling cavity out of resonance, keeping the PR mirror misaligned. Finally, in October 2004, Virgo was locked in the *recycled* configuration for the first time: with the PR mirror aligned and controlled. An original locking technique, called *Variable Finesse*, was adopted: the interferometer is initially locked away from the dark fringe with a low recycling cavity finesse, keeping the PR mirror slightly misaligned, then this mirror is progressively aligned increasing adiabatically the recycling factor up to its maximum value [24].

Before reaching this result a serious obstacle was encountered: the light reflected back by the PR mirror, and then back scattered again into the interferometer, produced spurious beam interferences that prevented any successful locking. The immediate solution was to insert an optical isolator between the IMC and the PR mirror, reducing the available power of the beam entering the interferometer by about a factor of 10, down to 0.7 W. Virgo took data in recycled mode, with this reduced power, until fall 2005.

The problem of backscattering light attenuation was steadily solved in January 2006, after a shut-down period of about two months, installing a large Faraday isolator in vacuum, as part of a re-designed input optics system. Contextually, also the input beam matching telescope was changed to allow the substitution of the existing PR mirror, which was curved and made of several assembled parts, with a new standard Suprasil silica mirror, which is both flat and monolithic.

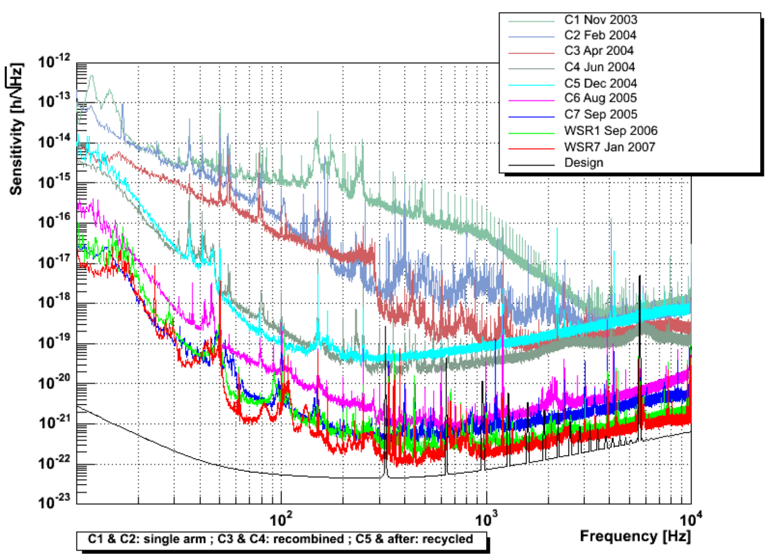

Figure5: The Virgo commissioning strain sensitivity since 2003

In April 2006 the laser power injected into the interferometer was about 7 W and the recycled power impinging on the beam splitter mirror was about 280 W. The increase of power was immediately followed by a loss of locking stability due to the increase of the mirror thermal deformation transients. Reducing slightly the power, and optimizing the cotrol filters and the procedures, a stable locking could be recovered. Actually a mirror thermal compensation system is under study.

Each Virgo commissioning progress was followed by data taking periods of a few days in well controlled conditions, to characterize the detector, to test its stability, and to measure the strain sensitivity. In September 2006, at the time of this conference, the transition to standard *science mode* data taking was prepared planning a series of monthly weekend science runs (WSR). In future a few months period of scientific data taking is foreseen for 2007.

The detector strain sensitivities, as directly measured during the commissioning, since 2003 until now, are shown in figure 5. The interferometer took data during the commissioning run *C5-C7* in recycled mode, with a beam power reduced to 0.7 W; while during the weekly science runs *WSR1-WSR7* the recycled interferometer operated with a 7 W high beam power. The sensitivity trend shows an improvement of the detector that goes together with the implementation or the improvement of the active controls and the operation of more complex optical configurations. Since the conference date the strain sensitivity in the frequency region below 200 Hz is limited by the excess of longitudinal and angular control noises, and still it is about a factor $10 \div 10^3$ below the target. On the other hand, in the high frequency region, above 500 Hz, the shot noise level is very close to its design limit.

4 Virgo data analysis

The Virgo sensitivity so far has not allowed any scientific search of real gravitational wave events; nevertheless a great deal of work has been devoted to settle the data analysis pipelines in view of the long data taking periods. A strong boost was also provided by the availability of real detector data from the commissioning and WSR runs.

In Virgo several working groups are involved in gravitational wave detection data analysis. Four main classes of gravitational wave sources are studied: there are working groups for burst, inspiral, pulsar and stochastic signals. The simulation and test of the gravitational wave detection algorithms is carried out on real data injecting fake event signals into the interferometer, using the mirror coil-magnet actuators, or adding them by software on the collected data.

Moreover another working group is dedicated to the identification of the detector noise sources, the characterization of the statistical properties of the real data, and the set-up of the veto algorithms and signals. Algorithms for the characterization of the noise distribution features are applied on collected data to identify the spectral lines of the sensitivity curve. All identified lines are catalogued and stored into a database.

Another major item is represented by the collaboration of the Virgo data analysis groups with the other gravitational wave detectors. As in other fields of applied physics, a network of widely spaced detectors is considered to be a powerful tool for filtering a wide class of fake events, to increase the observation time, and to enlarge the sky coverage. Moreover operating the detectors in a network will allow for the reconstruction of some important parameters of the sources, as its position and polarization [25] [26]. In this context Virgo has effectively started to co-operate with the Italian cryogenic resonant bar detectors for *burst* and *stochastic background* searches, while a *Memorandum of Understanding* for a joint detection in 2007 is being signed with LIGO.

5 Future perspectives and upgrades

Even if the Virgo interferometer has not yet reached its design performance the concept studies to enhance its detection capabilities have never ceased, and some preliminary indications are commonly accepted. This effort is well conceived considering that the rate of detectable gravitational wave events is increased by three orders of magnitude just enhancing the detector strain sensitivity by one order of magnitude.

A long term project for the so called *Advanced Virgo* detector is being discussed and the executive choices are planned by the end of 2007. The engineering phase is foreseen in 2009 and will necessarily require a long-term R&D activity .

On the other hand, another short-term plan of intermediate upgrades, for the so called *Virgo+* detector, have been conceived [27].

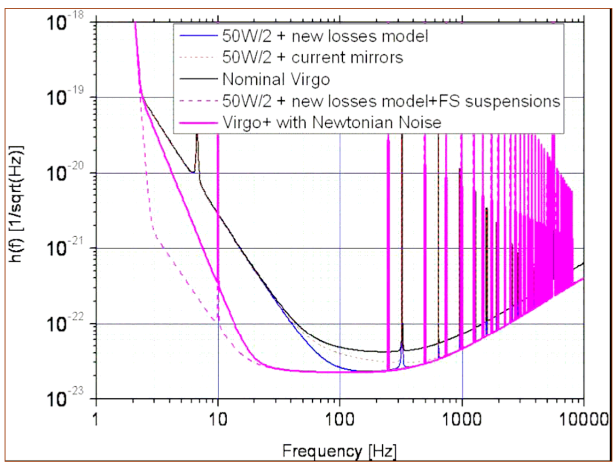

Figure6: Strain sensitivity comparison between the actual Virgo and the 50 W laser Virgo+

Taking advantage of the high performance of the SA suspension system the efforts are mainly oriented to the reduction of the thermal and shot noises limitations. These upgrades, being compatible with the present SA and with the optical lay-out systems, will require a short time to be implemented.

At lower frequencies the mirror *pendulum thermal noise* will be enhanced replacing the suspension last stage (Marionette, steel wires, and mirrors) with a *monolithic fused silica fibers suspension*. The mirrors will be suspended to the Marionette by fused silica fibers soldered on their substrate, reducing the wire friction and losses. A full scale prototype is already under test at the EGO facility to investigate the technical feasibility and the robustness of the fibers assembly. Also the *substrate thermal noise* of the present Fabry-Perot cavity end mirrors, made of *Herasil* silica, will be reduced replacing them with lower-loss *Suprasil* silica mirrors.

At higher frequencies the *shot noise* limit will be reduced by increasing the laser power. In figure 6 the expected enhanced sensitivity, for the case study of a 50 W laser, is shown.

Also the control system electronics will be upgraded to reduce the control noise and to update the components.

Virgo+ is expected to be implemented in 2008.

6 Conclusions

In October 2004 Virgo was locked for the first time in recycled configuration with an input beam power of 0.7 W. In April 2006, after some major upgrades of the detector input optics, the power of the input beam was rised to about 7 W.

Since September 2006, at the time of this conference, a new set of scientific data takings were performed. The detector strain sensitivity has progressed, but still remains to gain one to three orders of magnitude in the frequency region below 200 Hz, where an excess of control noise is dominant.

The activity on data analysis is going on, settling gravitational wave search pipe-lines, algorithms and vetoes, and identifying the detector noise sources.

The transition towards a long stable period of scentific data taking is being prepared. A first long data taking, in coincidence with the LIGO detectors, is foreseen for 2007.

After this significant step there will occur a short term shut-down to implement all the intermediate upgrades which are planned for Virgo+.

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