Status of Virgo

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The gravitational wave interferometer Virgo is presently in its commissioning phase. The status of the detector will be presented, focusing attention on the results obtained during this last year of commissioning activity, running the interferometer in the \textit{recombined} configuration (a Michelson interferometer with Fabry–Perot cavities in both the arms) and finally recycling the light beam into the interferometer.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

Virgo, consisting mainly of a recycled Michelson interferometer with Fabry–Perot cavities in the arms, aims to detect gravitational waves emitted by astrophysical sources [1] in a frequency range between a few Hz and a few kHz. The passage of a gravitational wave can be detected in the output interferometric signal as a relative displacement of a set of quasi-free falling masses (suspended mirrors). Other detectors, such as LIGO [2], TAMA [3] and GEO [4], are based upon the same principle. The Virgo design sensitivity is shown in figure 1. The main limiting noise contributions are seismic disturbances below 4 Hz, thermal noise up to 100 Hz and shot noise at higher frequencies.

The Virgo set-up has been designed to minimize the contamination of the output interferometric signal by the different sources of noise, in order to reach the planned sensitivity.

2. Virgo general layout

The final Virgo optical layout is shown in figure 2: a laser beam (20 W at 1064 nm) is produced by a Nd:YVO\textsubscript{4} high power laser injection, locked to a 1 W Nd:YAG master laser. The laser light is modulated in phase at 6 and 14 MHz before entering the vacuum system at the injection bench (IB), and is then \textit{pre-stabilized} by the 144 m long input mode-cleaner (IMC), using a standard Pound–Drever–Hall (PDH) scheme [7, 8]. The low-frequency stabilization is performed by actively controlling the length of the IMC to lock the laser frequency to the length of a 30 cm monolithic triangular cavity (RFC) suspended in vacuum. A 10 W power beam emitted from the injection system enters into the interferometer (ITF) through the power-recycling mirror (PR). The beam is split at the level of the beam-splitter mirror (BS), and enters the two 3 km long Fabry–Perot cavities (\textit{north cavity} and \textit{west cavity}). Together with the PR mirror, the Michelson ITF forms a Fabry–Perot cavity, the \textit{power recycling cavity},
Figure 1. Virgo design sensitivity with the limiting noise sources: seismic noise up to 4 Hz, thermal noise up to 100 Hz and shot noise at higher frequencies.

Figure 2. Virgo optical layout.

with an optical recycling gain of 50 when the ITF is at its working point. In this state, the expected power upon the BS is 500 W. The 3 km Fabry–Perot cavities have a finesse of 50 (optical gain about 32): the final power circulating inside the ITF is therefore estimated to be
Figure 3. Last stage of the Virgo SA.

around 16 kW. With the ITF at the operating point, the gravitational wave signal is extracted on the dark port beam, which is leaving the vacuum via the so-called detection bench (DB). Here the main beam passes through an output mode-cleaner (OMC), before reaching a set of 16 InGaAs photodiodes (B1), by which the dark port signal is reconstructed. Other signals are extracted from the ITF, essentially for control purposes: figure 2 shows the benches detecting the beams transmitted by the long Fabry–Perot cavities (NB and WB), the beam reflected by the ITF (DT), and the beam reflected by the second face of the BS (EB).

Concerning the seismic isolation, the Virgo suspension system differs from the other similar detectors. All of the large optics are suspended in an ultra-high vacuum system by the Superattenuator (SA), multipendulum isolators that are able to reduce seismic noise by a factor of $10^{12}$ at a few Hz thus enabling a high sensitivity down to a very low frequency [5].

The SA consists mainly of an inverted pendulum, a chain of seismic filters connected to one another by metallic wires, and the last stage, where the mirror and a reference mass are suspended from a so-called marionette (figure 3). Longitudinal and angular forces can be applied to the mirror by coil-magnet actuators, which are attached to the reference mass and the mirrors respectively. In a similar way, longitudinal and angular forces can be applied at the level of the marionette.

3. Virgo control systems

3.1. The longitudinal control

The nominal sensitivity of an interferometric detector such as Virgo is achieved by selecting an appropriate working point, with laser light resonant in the optical cavities, and the output port tuned on the dark fringe. These conditions translate into fixed relationships between the laser light wavelength and four independent lengths of the ITF [6]:

- the length of the recycling cavity ($PRCL$),
- the differential length of the short Michelson arms ($MICH$), $l_1 - l_2$;
• the common (CARM) and the differential (DARM) length of the two long arms, $L_1 + L_2$ and $L_1 - L_2$.

While the expected sensitivity is of the order of $10^{-18}$ m Hz$^{-1/2}$, the allowed deviation from the working point is $10^{-12}$ m rms. A feedback control system is needed to keep the ITF locked on the required interference conditions. Relative displacement of the mirrors is detected using a carrier beam phase modulated at 6 MHz (the frequency is tuned to be resonant in the IMC). Using a standard PDH technique all the lengths involved can be reconstructed by mixing the signals produced by the photodiodes, which are placed at different output ports of the ITF. These error signals are digitized and sent to the Virgo global control system (Global Control [6]), which computes the corrections to be applied to the mirrors by the actuators at the level of the reference mass.

A local control system, referred to the ground, is active in the bottom part of each SA in order to keep the longitudinal displacement of the mirrors below 1 $\mu$m rms. This also keeps the local angular motion of the mirrors below 1 $\mu$rad rms and allows the acquisition of the longitudinal lock of the interferometer using a limited actuation force, thus preventing noise reintroduction in the detection band.

3.2. The automatic alignment

Once the interferometer is longitudinally locked on its working point, an angular control system is needed to maintain the mirrors in an aligned position with respect to one another and the incoming beam. The automatic alignment scheme designed for Virgo [10] uses the Anderson technique [9]. The modulation frequency is chosen so that the first-order transverse modes (TEM$_{01}$) of the sidebands are resonant in the arm cavities. The transmitted light is detected by differential wave-front sensors, producing photo currents which are demodulated and then opportuneely mixed to achieve signals proportional to the misalignments between the optical components. These signals are then filtered and sent by feedback to the mirrors at the level of the marionette with a control bandwidth of a few Hz, so that noise is not reintroduced in the detection band. At the same time the local angular controls of the mirrors, to be controlled by the automatic alignment, are switched off.

3.3. The frequency servo

The pre-stabilization of the laser frequency 2 is used during the lock acquisition phase. Once the interferometer is controlled in all longitudinal degrees of freedom, a more complex frequency stabilization scheme is adopted, as will be described in section 5.1.

4. The commissioning of the 3 km long VIRGO

In order to test the stability and robustness of all of the sub-systems involved in the operations and to get some experience in designing the various control systems, the Virgo commissioning activity has been organized in steps of increasing complexity: the separate commissioning of the North and West Fabry–Perot cavities, followed by the commissioning of the recombined Michelson Fabry–Perot ITF, and eventually the commissioning of the recycled Michelson Fabry–Perot ITF. Short periods of continuous data-taking (the so-called commissioning runs) have taken place every two to three months since November 2003, in order to check the evolution of the detector and the consequent progress in the level of sensitivity. Five commissioning runs have been performed so far:
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- C1—north cavity longitudinally controlled (14–17 November 2003);
- C2—north cavity longitudinally controlled, plus automatic alignment (20–23 February 2004);
- C3—two configurations: north cavity as in C2 plus the frequency stabilization servo (23–26 April 2004); first data-taking with the ITF locked in recombined mode (26–27 April 2004);
- C4—ITF longitudinally controlled in recombined mode, with suspension tidal control, automatic alignment on both the arms, frequency stabilization servo (24–29 June 2004);
- C5—two configurations: ITF in recombined mode as in C4, plus end suspensions with full hierarchical control (2–6 December 2004); first data-taking with the ITF locked in recycled mode (6–7 December 2004).

The commissioning of a single arm was concluded with C3, with an automatic alignment and a frequency servo running for this configuration. The evolution of the detectors working in recombined and recycled modes will be described in sections 5 and 6, where the attention will focus upon the two most recent data-takings during C4 and C5.

5. The recombined interferometer

As an intermediate step towards the full configuration, the interferometer was commissioned in recombined mode for a large part of 2004. In this mode the optical scheme differs from the final configuration in that the PR mirror is significantly misaligned, so that only three lengths instead of four have to be longitudinally controlled: CARM, DARM and MICH. Using the end transmitted signals the two long arms can be controlled independently, acting on the corresponding end mirrors. As soon as the cavities are locked, MICH is controlled with the dark port demodulated signal (or alternatively the reflected demodulated signal), filtered and sent to the BS. By applying this strategy the lock is usually acquired in a few seconds.

Because of the low power upon the end photodiodes, the transmitted signals are electronic noise-limited: once the lock is acquired, they have to be replaced by another set of less noisy signals. In a steady state CARM is also attained using the in-phase demodulated component of the light reflected by the ITF. Instead, DARM is attained by the in-phase dark port light, which is slightly contaminated by MICH, mainly provided by the other quadrature of the ITF reflected light. Linear combinations of the error signals are computed to provide the correction forces to the mirrors. This phase is called linear locking.

5.1. The commissioning run C4

During C4, the interferometer was operated for five days in recombined mode. The longitudinal degrees of freedom were locked according to the linear locking scheme previously described, with the automatic alignment running on both arms and suspension tidal control on the end mirrors. The laser frequency was actively stabilized on CARM, which was locked on the reference cavity in line with the frequency servo strategy developed in Virgo, the so-called second stage of frequency stabilization. The OMC was locked on the dark fringe, so that DARM could be controlled by the filtered output demodulated signal. The interferometric scheme in the data-taking mode is described in figure 4.

The duty cycle of C4 is shown in figure 5: the longest continuous lock was about 28 h. All nine lock losses that occurred were analysed and understood, one of them due to an excess of seismic noise (earthquake in Alaska), the other ones mainly due to the incorrect
Figure 4. C4 configuration: the data-taking mode consisted of the ITF locked in recombined mode according to the linear locking scheme, with the automatic alignment running on both arms. In this state, the frequency stabilization control system is engaged. With the laser frequency pre-stabilized on the IMC, the CARM locking loop is switched off and the corresponding PDH error signal is added into the error point of the IMC-loop, giving a total bandwidth of 10 kHz. The same signal is applied to the length of the IMC, with a bandwidth of about 200 Hz: in this way the laser frequency and the length of the IMC are stabilized on CARM, which provides a better frequency stability at frequencies higher than the internal resonances of the SA. The low-frequency stabilization is achieved locking CARM on the RFC length.

Figure 5. Spectrogram of the dark fringe signal in C4. The vertical red bands correspond to lock losses. At the beginning and at the end of the run calibration noise injection and other special tests (acoustic noise injection in laser and detection laboratories, software and hardware injection of inspiral events) were performed.
auto-centring of the wave-front sensors. At the beginning of the run some acoustic noise injection was performed in the laser and detection laboratory, to study the possible couplings with the dark fringe signal [11]. A software and hardware injection of inspiral events was also performed [12] during the data-taking, to test some of the elements of the analysis chain and to characterize the detector stability during the run.

At the beginning of the run some calibration noise injection was performed in order to produce the sensitivity curve. The result is plotted in figure 6, together with the main noise contributions. The sensitivity is still limited by control noise at low frequency, by the mirror actuator noise in the intermediate frequency range and by laser frequency noise, starting from some hundreds of Hz.

5.2. The full hierarchical control of the SA

Longitudinal control during C4 was acquired and maintained by acting on the mirror at the level of the reference mass. The noise injected by the recoil mass actuators into the interferometer is a severe limit to the sensitivity of Virgo: at 100 Hz it is more than 1000 times larger than the design sensitivity. It is mainly contributed to by the 16 bit DAC noise (300 nV Hz$^{-1/2}$) and the coil driver noise (70 nV Hz$^{-1/2}$) and is converted into equivalent mirror displacement by a reasonably large coupling factor: 130 $\mu$m V$^{-1}$. Such a large coupling factor has been adopted in order to ease the lock acquisition. Once the lock is acquired, the residual force to be exerted is largely in the low-frequency region (dc–5 Hz), where tidal drifts and resonant motion have to be compensated, and very small elsewhere. Therefore, the gain of the coil driver (and the corresponding noise) cannot be reduced, unless a large fraction of the low-frequency force is reallocated to the upper stages. This is in fact the Virgo suspension hierarchical control strategy: once the lock is acquired, the locking force is split over three actuation stages in a hierarchical way. The correction in the range dc–0.01 Hz, that compensates for earth tides, is reallocated upon the soft inverted pendulum; the force in the range 0.01–8 Hz, where all the suspension resonances fall, is reallocated to the marionette. Consequently, the residual
The lock acquisition of the recycled ITF

As Virgo and LIGO have similar optical set-ups, the lock acquisition strategy developed [13] and adopted in the LIGO interferometer [14] was taken as a starting point for the lock acquisition scheme of the Virgo recycled interferometer. This baseline technique consists in sequentially controlling the four degrees of freedom of the ITF, dynamically changing the optical sensing matrix to compensate the variation of the fields in the course of lock acquisition. The technique had been experimentally tested on the Virgo ITF for about one month, and it was extremely important in order to check the robustness and the stability of all of the ITF sub-systems and to develop ideas suited to the Virgo characteristics, such as the use of the reflected 3f-demodulated signal (used in the TAMA scheme [15]) to control the recycling cavity length.

In the summer of 2004, during this period of experimental activity, it was observed that, with the PR mirror aligned, the light going back from the ITF to the IMC was back-scattered and re-entered the ITF, disturbing the control system error signals. Before the installation of a Faraday isolator between the IMC and PR mirror, a temporary solution was adopted: one of
the mirrors of the input telescope was replaced with one with only 10% reflection, reducing the light reflected to the IMC by two orders of magnitude, but at the cost of reducing the power inside the ITF by a factor 10.

Some intermediate stable states were locked applying the LIGO strategy, and some full lock acquisition trials were performed. At the same time an alternative technique was developed: the first tests rapidly provided promising results, and the experimental activity on the baseline technique was subsequently interrupted.

6.1. Variable finesse lock acquisition

The basic idea of the new lock acquisition technique is that the ITF is locked outside the working point for the dark fringe. In this way a good fraction of light escapes through the dark port and the power build-up in the recycling cavity is low. Then the ITF is adiabatically brought on to the dark fringe. This technique is referred to as variable finesse, because the finesse of the recycling cavity changes during the lock acquisition path. The procedure starts with the PR mirror slightly misaligned by some $\mu$rad. The simple Michelson is controlled on the half fringe, using the dark port dc signal, while the two arms are independently locked using the end photodiodes, as in the recombined configuration. The small quantity of light reflected by the interferometer in this configuration is used to control the recycling cavity power length by the $3f$-demodulated signal. In this way all the four longitudinal degrees of freedom of the ITF are locked in a stable way from the beginning of the lock acquisition procedure, preventing excitation of the mirrors. From this starting condition the PR is realigned, while always maintaining the Michelson on the half fringe, giving a very low recycling gain.

In order to increase the recycling gain the Michelson has to be brought on to the dark fringe: this is done adiabatically, decreasing the offset in the Michelson error signal. At the same time, the control scheme changes. The end photodiodes can only be used to independently control the cavities when the ITF is far from the dark fringe: when nearing the dark fringe they begin to couple strongly and a common and differential control has to be activated to keep the lock. Then a frequency stabilization servo is engaged, controlling CARM with a very high bandwidth: consequently, the contamination by this degree of freedom on all the photodiodes is cancelled. DARM is kept in a locked state by one of the end photodiode signals. The final
step consists of switching from the dc to a demodulated signal to control the Michelson length. Eventually the offset in the Michelson error signal is removed, the ITF goes on to the dark fringe and the recycling cavity gain increases up to the maximum value.

Applying this technique the lock acquisition of the full Virgo ITF was reached for the first time on 26 October 2004, and tested in the latter part of C5. A typical lock acquisition sequence, shown in figure 8, takes a few minutes and it provides a deterministic and repeatable lock. The final recycling cavity gain was measured to be around 25.

7. Conclusion

The 3 km Virgo detector has been in commissioning for about one and a half years. The first lock of a single Fabry–Perot arm was realized in October 2003: after exactly one year, the lock of the recycled ITF was performed (see figure 9). In between, the commissioning of the recombined ITF was also realized, with development of the various sub-systems involved in the operations and a designing of the main Virgo control systems: longitudinal lock, automatic alignment, frequency stabilization servo and full hierarchical suspension control.

Presently, the commissioning of the recycled ITF is on-going, with the goal to improve the robustness of the longitudinal lock and to put into operation the other main control systems successfully implemented in the recombined configuration. The characterization of the noise contributions to the sensitivity constitutes another fundamental task, with the prospect of a science run before the end of 2005.

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References

[1] Bradaschia C et al 1990 Nucl. Instrum. Methods Phys. Res. A 289 518–25
[2] Sigg D et al 2002 Commissioning of the LIGO detectors Class. Quantum Grav. 19 1429–35
[3] Ando M et al 2002 Current status of TAMA Class. Quantum Grav. 19 1409–19
[4] Willke B et al 2002 The GEO 600 gravitational wave detector Class. Quantum Grav. 19 1377–87
[5] Ballardin G et al 2001 Measurement of the VIRGO superattenuator performance for seismic noise suppression Rev. Sci. Instrum. 72 3643–52
[6] Cavalier F 2001 Le controle global deand Virgo These d’Habilitation a diriger des Recherches Université de Paris Sud, LAL 01-69
[7] Pound R V 1946 Electronic frequency stabilization of microwave oscillators Rev. Sci. Instrum. 17 490–505
[8] Drever R W P et al 1983 Laser phase and frequency stabilization using an optical resonator Appl. Phys. B 31 97–105
[9] Anderson D Z 1984 Alignment of resonant optical cavities Appl. Opt. 23 2944–9
[10] Babusci D, Fang H, Giordano G, Matone G, Matone L and Sannibale V 1997 Alignment procedure for the VIRGO interferometer: experimental results from the frascati prototype Phys. Lett. A 226 31–40
[11] Acernese F et al 2005 A first study of environmental noise coupling to the Virgo interferometer Class. Quantum Grav. 22 S1069
[12] Acernese F et al 2005 Inspiral analysis of the Virgo commissioning run 4 Class. Quantum Grav. 22 S1139
[13] Evans M 2001 Lock acquisition in resonant optical interferometers PhD Thesis Caltech
[14] Evans M et al 2002 Lock acquisition of a gravitational-wave interferometer Opt. Lett. 27 598–600
[15] Arai K and TAMA collaboration 2002 Sensing and controls for power-recycling of TAMA300 Class. Quantum Grav. 19 1843–8