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Virgo status

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Abstract
The Virgo collaboration has just concluded its first long science run (VSR1). In these four months the detector achieved a good duty cycle, larger than 80%, and an average horizon distance for binary neutron star system sources of about 4 Mpc. An intense commissioning activity was resumed after the run was complete to further increase the performances of the detector and to prepare the Virgo+ upgrades. The detector performances during the first science run and the last commissioning achievements are briefly discussed here.

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

1. Introduction

Virgo [1] is one of the largest ground-based interferometric gravitational wave detectors. The Virgo collaboration has put in a lot of effort in order to achieve significant progress in the commissioning of the detector. That allowed us to achieve the important goal of the first Virgo science run (VSR1) [4] this year. The antenna had been running in science mode for more than four months in 2007, close to its design sensitivity. After VSR1 the commissioning activity was restarted to further improve the detector sensitivity. The road map includes a shutdown in 2008, in order to upgrade the interferometer, to the Virgo+ configuration [5]. A sensitivity exceeding the Virgo design is expected. After this phase a second science run has been planned for 2009. For 2011 another major upgrade is being planned to bring Virgo+ to the advanced-Virgo configuration, the detector level of second generation.

In the second section of this paper a VSR1 run summary is provided, while the third section focuses on the detector improvements achieved in this period. The fourth section is devoted to post VSR1 activities and Virgo+. This paper concludes with a brief description of the future advanced-Virgo project [6].

2. The first Virgo science run

The VSR1 started on 18 May 2007 and ended on 1 October 2007. In figure 1 the sensitivity at the end of the run (in purple) is shown. The run was organized with three shifts per day,

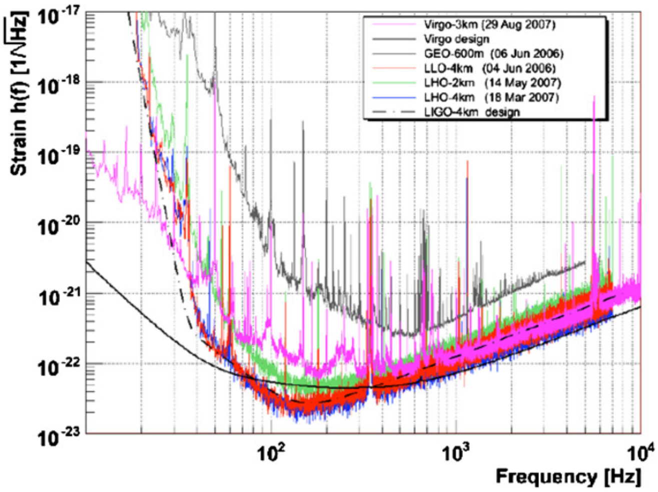

Figure 1. In this figure Virgo detector sensitivity is shown together with sensitivities of LSC detectors at the time of S5 run.

Figure 2. Duty cycle evolution during VSR1. The two lines represent the integrated duty cycle (continue-red line) and duty cycle per week (blue line). The Virgo interferometer was locked for the 84% and in science mode for 81% of its time.

(This figure is in colour only in the electronic version)

involving one operator and one scientist with one weekly coordinator. During the data taking some periodic operations were performed, such as calibration (1.5 h/week), commissioning (6 h/week), hardware injections and maintenance (4 h/week) of vacuum, infrastructure and commissioning investigation and fixes. In particular the commissioning activities turned out to be crucial in improving the detector performance during the run.

An agreement between LSC and the Virgo community exists, finalized to the data sharing and joint data analysis. The Virgo science run took place in coincidence with the last months of the science run S5 of the LIGO and GEO detectors [2, 3]. For instance figure 1 shows a comparison between detector sensitivities at the time of the S5 run. The Virgo detector was already matching the LIGO H1 during the VSR1 at high frequency, performed better at frequencies below 40 Hz, but was noisier in the intermediate frequency band, where the Virgo sensitivity curve is expected to run higher than in LIGO anyway, by design. At present, in that frequency region, the Virgo sensitivity is less than one order of magnitude worse than both its design and LIGO actual sensitivity.

In figure 2 the integrated locking duty cycle and the duty cycle per week are shown. At the end of the VSR1, Virgo was locked for 84.2% of the time and in science mode for 81.0%

of the time. It was possible to achieve such a high efficiency because the Virgo detector was capable of maintaining long locking periods.

The main causes of unlocking can be either technical or environmental. In the first category we can consider the scheduled maintenance and commissioning activities, but also global control software crashes. In the second category earthquakes and bad weather conditions were by far the most significant.

2.1. VSR1 duty cycle improvements

The robustness of the Virgo locking depends mostly on environmental factors. Mirror oscillations of frequencies below 1 Hz are induced by bad weather conditions such as strong winds or sea activity. Typically, these effects degrade the detector sensitivity, without causing unlocking; vice versa, unlocks happen in coincidence with earthquakes of magnitude 6 or higher anywhere taking place on Earth.

As mentioned above, earthquakes caused several unlock events per week. Due to such events, mirror suspensions became excited and took a couple of hours to relax to a stable condition. This further delayed re-locking, thus reducing the interferometer duty cycle. For this reason, a considerable effort was made to improve the suspension control system during the VSR1. As a first step we implemented the so-called earthquake guardian, to switch automatically to more robust controls. Next we implemented a suspension differential control, which is immune to the common displacements that characterize the earthquake action on the interferometer. Micro-seismic activity in the 0.2–0.6 Hz range, usually peaked at 0.3 Hz, affected the mirror motion and consequently ITF sentivity. It is possible to build micro-seismic-free signals by exchanging the signals (position and acceleration) among the suspensions. In the central area this allowed an increase in the crossover frequency of hybrid error signals used for BS (beam splitter) and PR (power recycling) for top-stage control up to 100 mHz, while for end towers (NE, WE), where the result is obtained through the reallocation of ITF lock force to top stage, the crossover was kept at 70 mHz. The overall result is that the noise induced by the ground on accelerometers is below or close to what would affect a standalone suspension by means of 30 mHz crossover, but without spoiling the top-stage control with the tilt noise due to accelerometers in case of wind. Such a differential control (global inverted pendulum control) gave a 2–3 times increase in robustness against earthquakes. This new suspension control system links the control of the interferometer mirrors to the input mirrors, instead of having independent local sensors on each mirror. After these interventions the rate of unlocking events was reduced to below one per week. In figure 3 the ground displacement robustness of the super-attenuator evolution is shown. It is possible to observe how in the first part of the run unlocks were induced by displacements close to 10 μm, while the interferometer was able to stay locked for displacements 2–3 times larger after the earthquake guardian and suspension differential control had been implemented. In this figure the two implementation phases are shown. In the figure, the triangles are associated with ITF unlock due to earthquake events, while empty circles are the events at which ITF survived and the shadow area is just the average of such events.

2.2. VSR1 sensitivity improvements

During the VSR1 many commissioning activities were devoted to sensitivity improvements, in particular in the intermediate and low frequency range. An important tool to achieve such a goal was the implementation of the automated noise budget measurements, which allows us to speed up ‘noise hunting’. After having determined the transfer function from control to

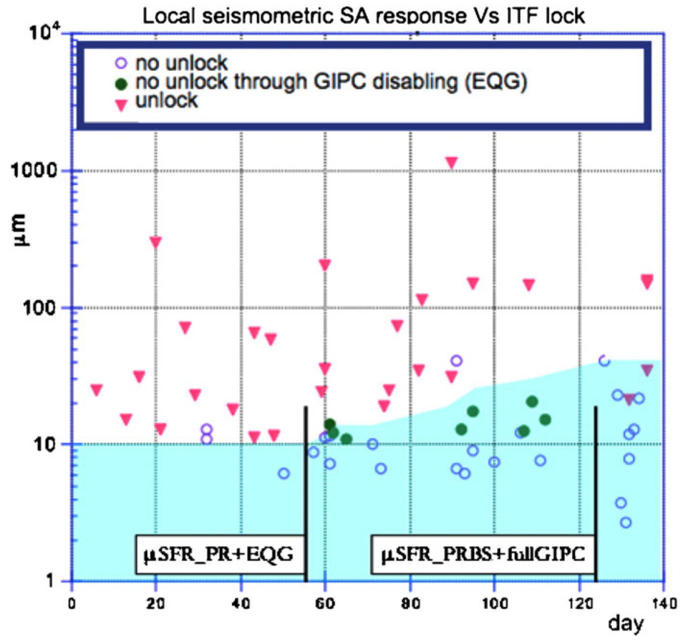

Figure 3. Super-attenuator response and interferometer unlocking conditions versus time. In the last part of the VSR1 the SA was able to survive to 2–3 times higher displacements.

gravitational wave signal by injecting colored noise, the spectrum of the very same control noise was used to determine its contribution to the dark fringe spectrum.

The noise of the alignment system limits the present sensitivity below 20 Hz. The control filters therefore have been re-configured, in the effort to optimize the trade-off between low frequency gain and high frequency roll-off. Moreover, the angular noise–dark fringe coupling was reduced by centering the beam on the mirrors.

As mentioned above, environmental noises are a major limitation to the Virgo sensitivity. These noises are often connected to scattered light. The careful elimination of spurious beams and more rigid mounting of the optical components contributed to their reduction. Reporting such an issue, we made important advances as detailed in the following section.

Another task was the measurement of the magnetic noise, which was found to be responsible for several spectral lines in the 50–100 Hz region. These were suppressed by removing power supplies which were too close to the mirrors and interacting with the magnets glued on the mirror surface.

Improvements on Virgo sensitivity after the VSR1 in figure 4 are displayed. The effects of the most important actions are highlighted. In the intermediate frequency domain the noise due to piezo-actuator noise was isolated and removed. The improvement at low frequency, due to the commissioning activity on the beam centering control filter and on the loops of the longitudinal controls is clearly visible. The same shows the comparison of such results with the sensitivity curve at the beginning of the first run and from the Virgo design.

3. Horizon

The detector sensitivity can be effectively quantified by a single parameter as performance index. It represents the distance of a coalescing binary neutron star whose signal would

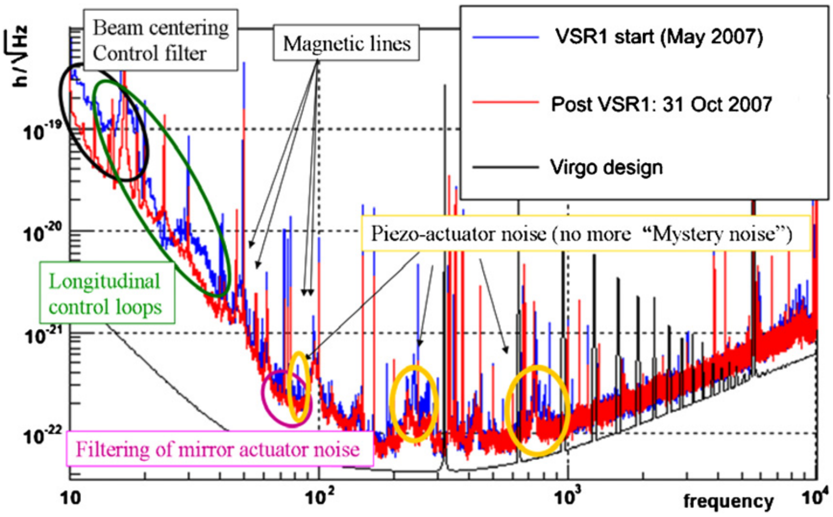

Figure 4. In this figure the Virgo sensitivity at the beginning of VSR1 and just after the science run are shown. Sensitivity improvements during VSR1 are clearly visible.

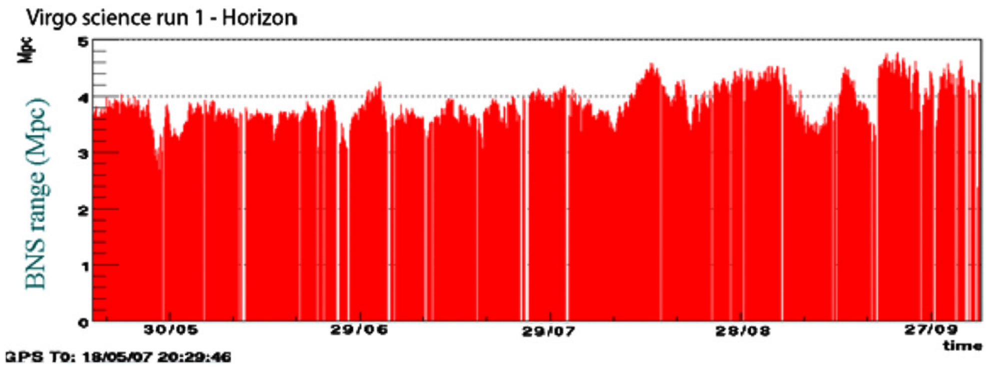

Figure 5. Horizon distance evolution during VSR1 is shown. The horizon is defined for coalescing binary neutron stars sources, averaged over sky position, inclination and polarization with signal-to-noise ratio of 8.

be seen with a signal-to-noise ratio of 8, averaged over source sky position, inclination and polarization. This number is called horizon. Figure 5 shows how the horizon distance evolved during the VSR1. In this plot the sensitivity improvements discussed in the previous section are visible as horizon distance increases. At the beginning of the run the average distance was close to 3.7 Mpc, while by the end of the run values higher than 4 Mpc were observed.

Several causes can affect the horizon stability: weather conditions are the most significant ones, but also alignment fluctuations and thermal effects in the input mirrors and detector control should be taken into account.

4. Activities after the VSR1

The first step after the end of the Virgo science run was a detector characterization in run condition for two weeks. A better knowledge of the detector response allowed verification of the calibration and preparation of the control loops optimization.

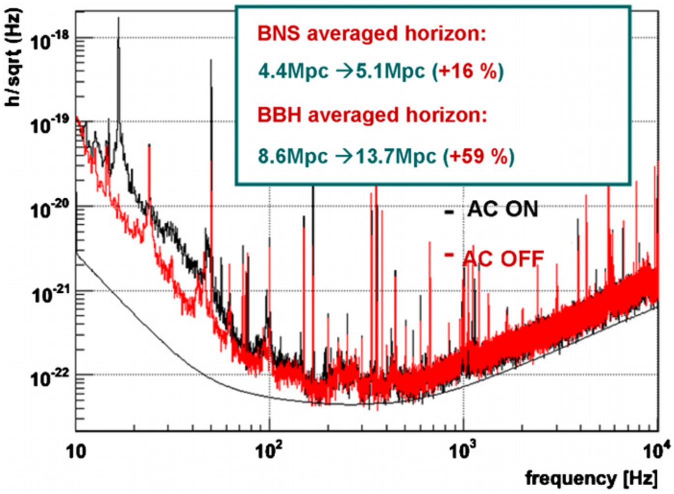

Figure 6. In this figure Virgo sensitivities with air conditioning on and off conditions are compared. A remarkable gain in the frequencies range below 60 Hz is visible.

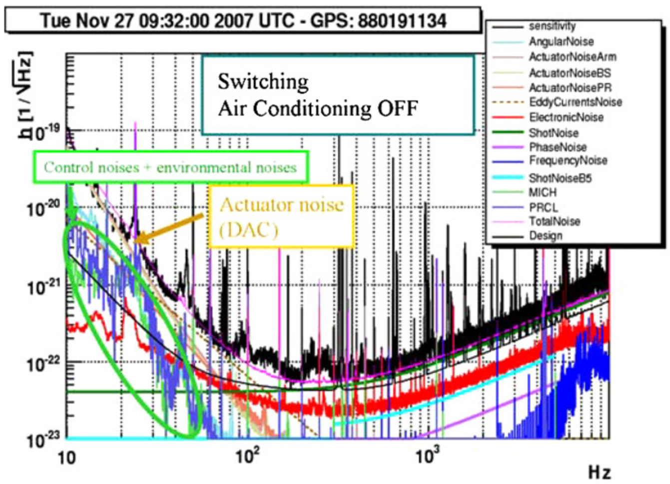

Figure 7. Noise budget of the Virgo detector with air conditioning off. The reduced noise is the control noise, coupled with the environmental noise.

The large effect of the environmental noise on the detector sensitivity is reported in figure 6, where the remarkable sensitivity gain obtained in the frequency range below 60 Hz is apparent. This test was made by switching off the air conditioning on November 2007, but further improvements have been achieved after that.

In the same figure the horizon gain for binary neutron star (BNS) and black hole (BBH) systems are shown for the two air-conditioning configurations (on/off). By switching off the air conditioning, the horizon increases by 16% for BNS and, even more remarkable, by 60% for BBH.

In figure 7 the noise budget with air conditioning off is shown. From this noise budget it is possible to discover that in this case the control noise (the main noise in this frequency band) is reduced, coupled with the environmental noise.

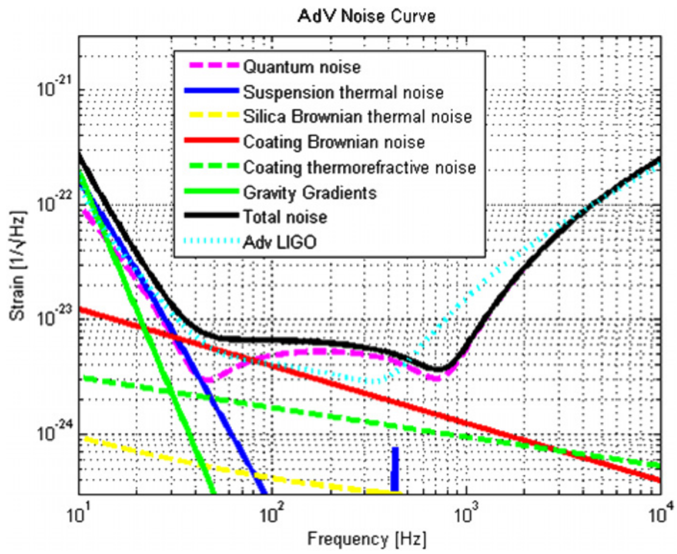

Figure 8. In this figure the advanced-Virgo conceptual design sensitivity is shown.

The next step is the understanding of the environmental noise coupling path, in order to reduce the environmental noise and the effects on the dark fringe. When this noise will be controlled, the next significative noise will be the well-known actuator noise.

5. Conclusions

At present the main goal of the Virgo collaboration is to reach the Virgo+ matching sensitivity and to get ready for next science run scheduled for mid 2009 in coincidence with eLIGO.

Just after the VSR1, at the end 2007, for a few months commissioning activity focused on the low-intermediate frequencies, in order to address the control and environmental noises. More activity is planned for 2008 on environmental noise mitigation and thermal compensation. The Virgo+ upgrade has been scheduled in May–June 2008. Some of the planned improvements are: upgrade new control electronics, laser amplifier (50W) and injection system optics compliant with 50W power, new mode cleaner end mirror and payload replacement. After upgrade the global commissioning will resume for about one year until mid 2009, when the VSR2 starts.

Looking beyond Virgo and Virgo+, it should be noted that the EGO Council endorse the advanced-Virgo project; hence the preparation for advanced-Virgo is now a priority. The goal is to improve sensitivity by a factor of 10 with respect to the nominal Virgo. A document describing the advanced-Virgo baseline design [6] has been released, together with preliminary budget and project execution plans. In figure 8 the advanced-Virgo design sensitivity is shown together with its noise budget and compared with the advanced-LIGO sensitivity.

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