VIRGO COMMISSIONING PROGRESS

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1 The Virgo project

Virgo is a 3-km gravitational wave interferometer, aimed to the detection of the gravitational waves emitted by astrophysical sources and built near Pisa, by a French-Italian Collaboration. Details about the gravitational waves sources, their detection through interferometric techniques, and the scheme of the Virgo detector can be found in the plenary session paper “The status of the Virgo gravitational wave detector”[1]. In the following we will focus only on the commissioning aspects.

2 Commissioning general path

The Virgo commissioning started in September 2003, when a first laser light was sent over one of the two 3-km long arms. Useful experience was acquired in 2001-2002 [2] during the commissioning of the central section of Virgo, even if the problems connected with a kilometric scale interferometer are very different.

The commissioning was organized in steps of increasing complexity: first the two 3-km Fabry-Perot cavities were studied independently (September 2003 – February 2004), then a Fabry-Perot Michelson interferometer was commissioned (February 2004 – October 2004), and finally the full Recycled-Fabry-Perot-Michelson interferometer (since October 2004). For each step, once the longitudinal lock was achieved under angular local controls, low noise robust operation was engaged by means of automatic alignment of the mirrors, laser frequency stabilization and suspension hierarchical control. The noise of the interferometer was then studied and reduced. Since several noises depend on the optical configuration (Fabry-Perot cavity, recombined), a more effective *noise hunting* phase started only when the full (recycled) interferometer was locked, in October 2004. Obviously, the control strategy and the noise reduction are strictly related. At low frequency the controls directly contaminate the sensitivity, while at high frequency several laser noises affect the interferometer output through angular and longitudinal accuracies. For this reasons, following the commissioning progress, the control design are constantly upgraded.

3 *Low power interferometer* and backscattering problems

The first part of the recycled interferometer commissioning was carried out with a reduced input power (about 0.8 W), obtained by attenuating the mode-cleaner transmitted power by one order of magnitude. This choice was motivated by the presence of backscattering fringes between the input mode-cleaner and the interferometer, due to the absence of optical isolation between these two elements. These fringes were the origin of large perturbations in the frequency of the laser and consequently of difficulties in the interferometer control.

The lock of the interferometer was achieved in October 2004, through an original technique, called *variable finesse lock acquisition* [3]. The commissioning with low power lasted for about one year (from October 2004 to September 2005) and during this period the automatic alignment was commissioned [4] as well as the frequency stabilization and the suspension hierarchical control.

Two data takings (C6, 2 weeks long and C7 5 days long), were performed between August and September 2005 [5,6], with duty cycles respectively of 90% and 65%. The sensitivity obtained is given in Fig. 1.

At the end of this phase the noise of the interferometer was almost completely understood, being control noise below 200 Hz and read-out (shot) noise above 200 Hz.

4 Injection bench upgrade

After the run C7 (September 2005), the interferometer was shut-down in order to allow the replacement of the injection bench and the installation of the Faraday isolator between the mode-cleaner and the interferometer. Due to the limited space it was not possible to install the Faraday isolator on the existing bench and a new one was built. This was also the opportunity to redesign some optical elements of the bench, to enlarge apertures and reduce diffused light, dump more effectively spurious beams and to host the full input matching telescope.

Along with the replacement of the bench, the power recycling mirror, made with a composite structure, was also replaced with a monolithic one, having a higher reflectivity and flat substrate.

The commissioning of the new injection system and the recovering of the control due to the power increase took about six months. In spring 2006 it was possible to relock the interferometer, with about 9 W input power.

5 *High power interferometer* and thermal effects

The power increase by an order of magnitude revealed unexpected problems. The mirrors are deformed by the heat absorbed, and this causes a change in the light wavefront, mainly visible in the sidebands, which resonate only in the central recycling cavity, that has nominal flat-flat geometry. The excess of absorption, with respect to the nominal value is not fully understood, but it can be related to mirror cleaness.

The thermal effects highly complicate the lock acquisition. First of all, the interferometer experiences a *thermal transient*, with a time constant of about 10 minutes. During this period the feedback loops (both longitudinal and angular) must deal with changes of the optical gains and phases of the interferometer signals, and react in order to keep the interferometer locked.

Other consequences of the thermal effects inside the interferometer are under investigation. Among them, the excess of noise due to wavefront deformation is not excluded.

In general the thermal effects slow down all the commissioning activity, partially because of the effort needed to achieve a robust operation of the interferometer, but also because of the time needed to reach a steady state, at least 30 minutes.

In September 2006 the complete recovering of the sensitivity (after the two major changes of the injection bench and power recycling) and robust operation, were achieved. The stored power was ~280 W, corresponding to 7 W input power and recycling factor about 40.

Substantial sensitivity upgrades have been performed between September 2006 and March 2007 (see Fig. 1), due to several improvements. The main ones are: frequency stabilization upgrades, reduction of longitudinal control noise, reduction of the oscillator phase noise due to better alignment stability, reduction of many environmental noise sources.

7 Week-end Science Run program

The Week-end Science Run program was started in September 2006, as a transitory phase between the commissioning and a long science run, planned for mid-2007.

The goal is to collect data for 56 hours during the week-end, and use them for data analysis studies and detector characterization. The schedule of the science run is decided following the commissioning activities, that remains the priority during this period. During each WSR the activity is organized in 8-hours shifts, covered by one operators and one scientist.

Nine WSRs have been performed from September 2007 to March 2007. The duty cycle ranges from 65% to more than 90% for WSR8 and WSR9. The longest lock was 55 hours (WSR9). The sensitivity evolution is given in Fig. 1.

The first WSRs and, more in general, the daily commissioning activity, were limited by a strong sensitivity to bad weather conditions. Wind and sea activity increase the seismic noise at very low frequency (10 mHz - 0.6 Hz). In order to deal with this problem a large effort was done both on the suspension control and on the automatic alignment. A substantial increase in the stability, duty cycle and data stationnarity was achieved between the first WSRs and the last ones.

8 Current status

The best sensitivity achieved is $\sim 10^{-22}$ $\mathrm{Hz}^{-1/2}$, at a few hundreds Hz. Above ~400 Hz sensitivity is mainly limited by the shot noise; below ~50 Hz is mainly limited by control noise. In the central region of the spectrum the sum of all the known sources of noise is still 2-3 times below the measured sensitivity. However, there are strong evidences that the environmental noise, coupled to the interferometer output through diffused light and spurious beams, is limiting the sensitivity in this region.

The reorganization of the optical benches and their acoustic isolation is on-going.

The commissioning activity and the WSR program will continue until mid May, when a long science run will start for about 4 months.

References

1. Acernese et al., *The status of the Virgo gravitational wave detector*, MG11 proceedings
2. Acernese et al., *The commissioning of the central interferometer of the Virgo gravitational wave detector,* Astroparticle Physics 21, 1-22 (2004)
3. Acernese et al., *The variable finesse lock acquisition technique,* Classical and Quantum Gravity, 2006.23 (S85-89)
4. Acernese et al., *The Virgo automatic alignment status*, Classical and Quantum Gravity, 2006.23 (S91-101)
5. Acernese et al, *Virgo Status,* Classical and Quantum Gravity, 2006.23 (S635-639)
6. Acernese et al., *Virgo data analysis for C6 and C7 engineering runs* , MG11 proceedings

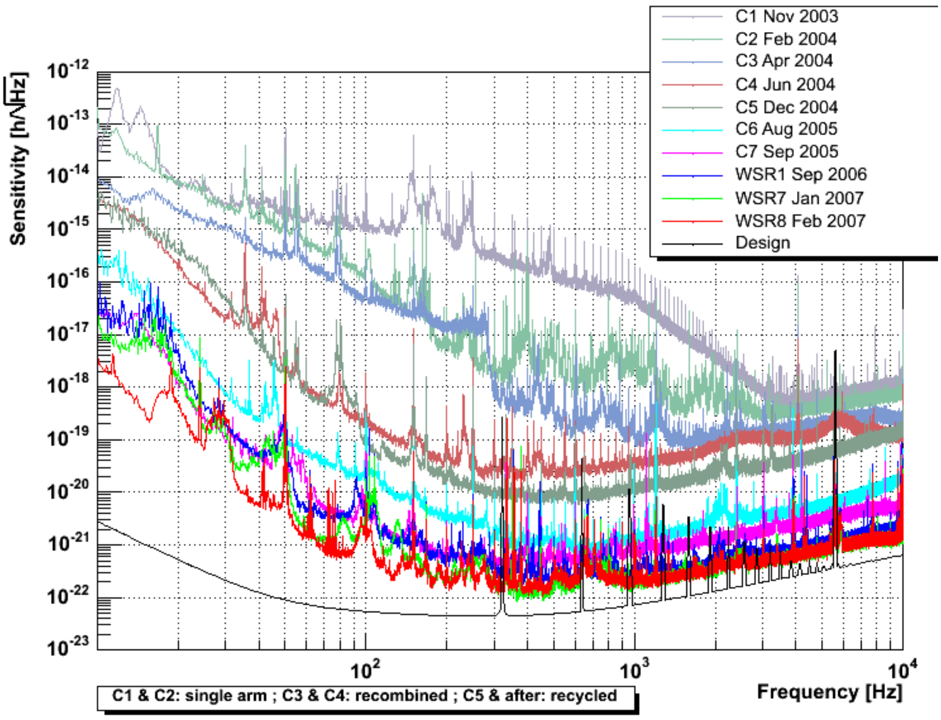

Figure 1. Virgo sensitivity evolution for the different commissioning runs and for some of the week-end science runs.