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The Virgo status

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Abstract
We report on the status of the Virgo detector, under commissioning. We will focus on the last year's activity. The two commissioning runs performed during 2005 allowed us to reach a sensitivity of $h \sim 6 \times 10^{-22}$. The data obtained during the runs were used to test a few data analysis algorithms, namely coalescing binaries and burst searches. The main improvements made on the detector during this year will be described, as well as the plans and activities foreseen in the coming years.

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

1. Introduction

Virgo is an interferometric detector with 3 km arms length. Its aim is to detect gravitational waves from astrophysical sources in a frequency range from a few Hz to a few kHz [1]. The nominal expected sensitivity is $h \sim 4.5 \times 10^{-23}$ at $\sim$260 Hz.

The detector is in a commissioning phase, having its final optical configuration. At the beginning of summer 2005, reasonable stability of the detector operation was achieved, which allowed for two commissioning runs, called 'C6' and 'C7'.

In this paper, we present the results of these runs, the ongoing improvements of the apparatus and some perspectives.

2. Status of the detector

2.1. Sensitivity evolution

Figure 1 shows the evolution of the sensitivity of Virgo since the first commissioning run in November 2003. During the run C7 in September 2005, a sensitivity which is a factor 10 worse than the nominal one at high frequency (above 300 Hz) has been obtained. The sensitivity reached during the C7 run was $h \sim 6 \times 10^{-22}$ at 300 Hz.

2.2. The commissioning runs C6 and C7

The target of run C6 was to test the improved stability of the system. This run started at the beginning of August and lasted 14 days, with an 86% duty cycle and improved overall performance. The main improvements that allowed this result were a preliminary automatic control of alignment drifts [2, 3] and the automation of the unlock-recover and re-lock procedure. The longest uninterrupted operation segment was 40 h.

Figure 2 shows the optimal horizon distance (distance of detection with a signal over noise ratio of 8 for an optimally oriented 1.4–1.4 $M_\odot$ neutron star–neutron star binary coalescence). Some improvements made during the run are clearly visible. The first one was a dump of stray light beams on one of the end mirrors (arrow *a* on the figure), the second was a realignment

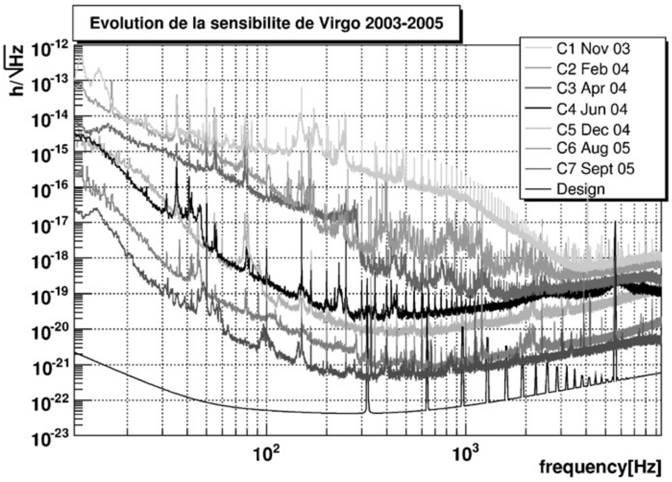

Figure 1. Virgo sensitivity evolution during the commissioning phase.

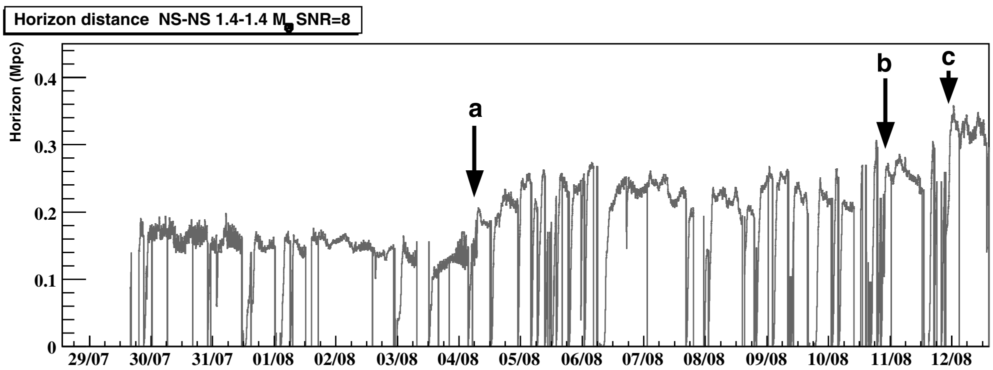

Figure 2. Horizon distance during the C6 commissioning run for an optimally oriented $1.4/1.4\ M_\odot$ NS–NS binary with SNR = 8. The arrows show the time of the main improvements made during the run.

of the beam on the input mode cleaner (arrow *b*), which laid to a reduction of the power noise and the third was an improvement in the power stabilization loop (arrow *c*).

By the beginning of September several improvements such as automatic alignment on 5 among 6 interferometer mirrors, shot noise reduction and control loop tuning were implemented. Then we performed run C7 aimed to test the optimized sensitivity. During this run, a horizon distance over 1 Mpc was reached (see figure 3), and the run lasted 5 days, with a duty cycle of 65%.

In figure 4, the noise budget obtained during the C7 run is presented [4]. It may be roughly divided into two parts. Below 300 Hz, the main contributions are due to control noise and angular alignment noise, while above 300 Hz, shot noise dominated. The comparison between the incoherent sum of all noises and the sensitivity shows that in general the noise budget is understood.

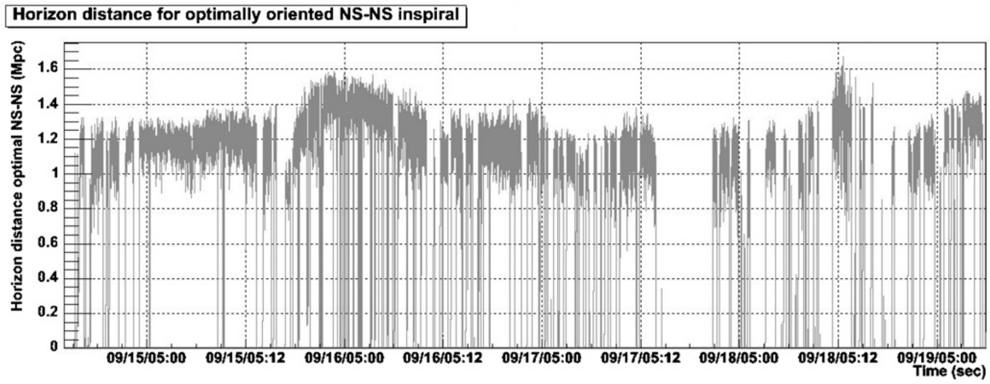

Figure 3. Horizon distance during the C7 commissioning run for an optimaly oriented 1.4–1.4 $M_\odot$ NS–NS binary with SNR = 8.

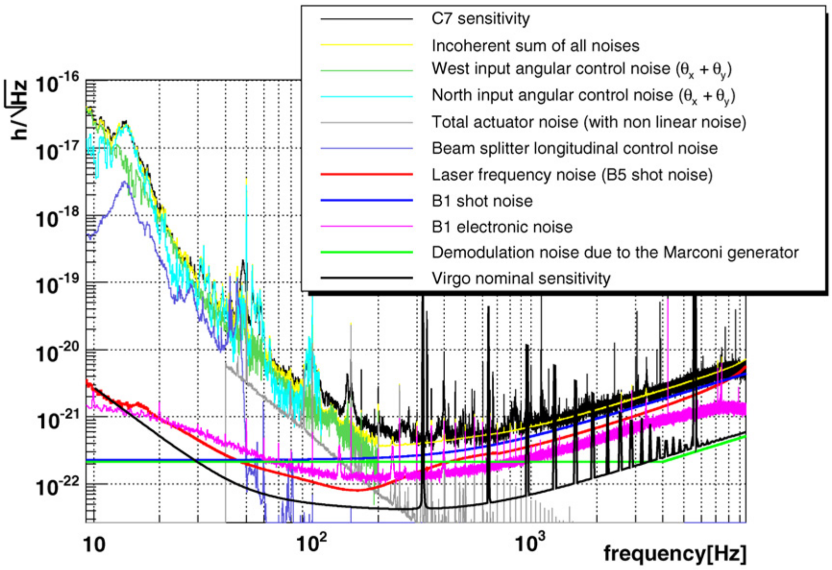

Figure 4. Noise budget of the detector during the C7 run.

2.3. Pending and foreseen improvements

During the year 2005, the beam power at the input of the interferometer, just before the recycling mirror, was attenuated by a factor 10 and limited to 0.8 W. This was due to light diffused by the mode-cleaner end mirror interfering with the main beam. After the C7 run, the solution was to replace the injection bench with a new one that includes a Faraday isolator in order to reach the 8 W power injected on the first mirror (power recycling mirror) of the interferometer. A better mechanical transfer function should improve the sensitivity at low frequency thanks to an easier control noise re-injection reduction.

Another important change was made by replacing the power recycling mirror. The new mirror has a larger diameter, better mechanical behaviour, and its reflectivity is higher—95% compared to 92% for the old one. The increase of the recycling factor combined with a reduction of the losses inside the injection system should lead to a power close to 500 W on

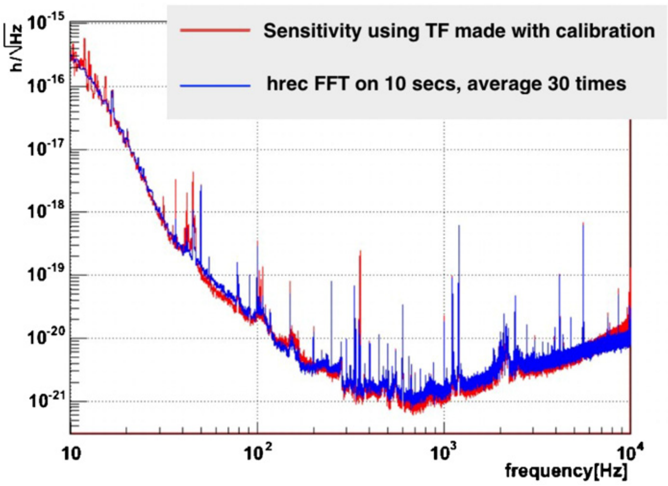

Figure 5. Comparison between a sensitivity curve obtained by the time-domain reconstruction used in Virgo and a sensitivity curve obtained using a transfer function measurement made with a complete calibration procedure.

the beam splitter, which represents a factor 20 increase if compared to the C7 case. The two improvements should decrease the shot noise level roughly by a factor 4.

Lastly, the commissioning activities include, among others, the improvement of the angular alignment, which should improve the sensitivity at low frequency, the dumping of the stray light, the reduction of the control noises and the improvement of the acoustic isolation.

2.4. Elements for the data analysis

We present a few elements that represent foundations for the data analysis activities.

2.4.1. Reconstruction. The reconstruction consists of the extraction of the arms length difference, i.e. the amplitude of the gravitational wave signal, from the dark fringe signal at the output of the detector [5].

In Virgo, this is done in the time domain. The dark fringe signal is corrected from the effects of controls (using actuator signals corrected from pendulum effects), and from the optical effect of the Fabry–Perot cavities. A few calibration lines are used to track the optical gains and should be removed by the reconstruction procedure. The amplitude of the remaining calibration signals is used as an error estimator. Figure 5 shows a comparison of the sensitivity obtained using the procedure outlined above under a Fourier transform, and the sensitivity coming out from a transfer function made with a complete calibration procedure in the frequency domain. The two results match satisfactorily.

The reconstruction runs online, which means that the analysis can run online starting from the *h* reconstructed channel. As a by-product, it is easy to obtain the NS–NS or black hole–black hole horizon to assess the evolution and performance of the detector. At the beginning of 2006, an optical calibrator will be used as an additional check.

2.4.2. Data quality. A set of flags is gathered by the data acquisition to assess the quality of the data. Starting from this set, a few web pages are generated which allow us to check the status of the interferometer online (figure 6), and a subset of instrumental vetoes are used to

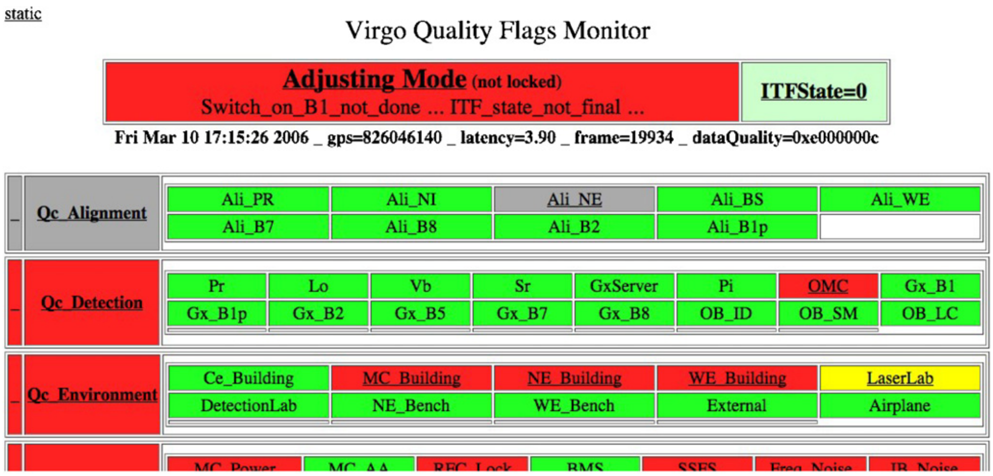

Figure 6. Example of a web page generated online from the data quality flags. The upper side bar shows that an operation parameter is under readjustment and the red blocks below emphasize the variables that exceed the given thresholds.

define a ‘science mode’. The ‘science mode’ flag is activated once all the quality flags ensure that the interferometer is operating accordingly to the expectations.

2.4.3. Noise studies. Noise studies were done using data including that collected during the C6 and C7 runs. They consisted of the identification of non-stationary processes, the search for transients and glitches to be used as data vetoes and the injection of acoustic and electromagnetic noise at given physical ports of the detector to check the effect in its output signal. Some environmental noises (lightning, etc) studies were also performed.

Some software tools were developed in this context, such as the Noise Analysis Package (NAP) [6], a general library for the noise analyses, and two catalogues for lines monitoring and transients identification.

2.4.4. Computing status. In the second half of 2005, the online data analysis computing hardware consisted of a farm of 32 Opteron 2 GHz bi-processor CPUs. This farm was used to run coalescing binaries search algorithms during the C6 and C7 runs. Between the runs, it was used to perform some off-line analyses, coalescing binaries searches as well as joint LIGO–Virgo analysis projects. An extension of the online data analysis farm is foreseen during 2006, which should triple the computing power.

The Bologna and Lyon computing centres were used to carry out periodic signal searches and burst analyses. The joint LIGO–Virgo effort also used the two computing centres facilities. It should be noted that the raw data from all the commissioning runs has been transferred to, and is accessible from, the computing centres.

3. Data analysis activities

3.1. Analysis of the data from commissioning runs

The data obtained during commissioning runs gave the opportunity to perform some analyses. The data of the C5 run (December 2004) were used to perform and test coalescing binaries, burst and pulsar searches. The pulsar searches were done on 1.4 days of C5 data.

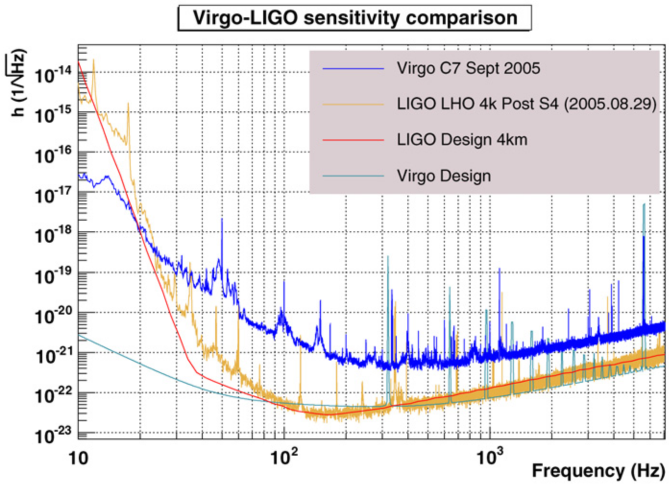

Figure 7. Comparison of LIGO and Virgo sensitivities at the end of summer 2005.

The analyses of C6 and C7 data showed the importance of veto definitions following the studies of non-Gaussian events in the noise. During C6 and C7, we used hardware injections of coalescing binaries and burst signals, which were analysed afterwards.

3.2. Comparison of the sensitivities of Virgo and LIGO

Figure 7 shows a comparison of the Virgo sensitivity curve, as of C7, and of the LIGO sensitivity obtained at the same period—the end of August 2005 [7]. While LIGO is very close to its nominal sensitivity, Virgo has a factor 10 to gain in the shot noise dominated region ($f > 300$ Hz) and a factor 10^2 to 8×10^3 elsewhere to reach the same goal. The improvements to the detector described in section 2.3 makes us feel confident that Virgo sensitivity will approach the nominal figure within 2006, in the high frequency region ($f >$ 300 Hz). This is especially relevant for burst searches, and the LIGO and Virgo sensitivity curves will be close enough to begin considering and exploiting the advantages of joint analyses.

3.3. Joint analyses

The joint analyses working groups were set up at the end of 2004 and during 2005 to foster and develop all the analyses needing a joint effort between Virgo and other gravitational wave detectors. The first part of this effort is setting up the methods of the joint analysis. Namely, once the performance of joint analyses versus each category of GW source has been assessed, we had to explicitly select the data channels to be exchanged, the means and the technology to do it.

The joint work pending with the LIGO Scientific Collaboration includes coalescing binaries and burst analyses [8, 9]. During 2005, a comparison of the search algorithms was made, as well as an implementation of coincidence analyses. The implementation of a coherent analysis is in progress.

Finally, a joint work with the Auriga and ROG collaborations [10] has started.

4. Future activities and plans

After the replacement of both the injection bench and the power recycling mirror, which lasted from the end of the C7 run to the end of 2005, the restart of the interferometer is ongoing since the beginning of 2006. The commissioning of the recycled interferometer will be the main activity during the first half of 2006. Data aquisition in science mode should then start during the quiet periods (week-ends, nights) and then become continuous for a few months near the end of the year. The goal is to reach a factor 10 on the NS–NS horizon distance with respect to the C7 run.

The Virgo collaboration has undertaken the study of upgrades in two steps. The first step, called Virgo+, consists of a set of medium scale improvements that will be limited to part of the detector in order to install them without the need for a long shutdown and recommissioning. These improvements include a laser power increase from 20 W to 50 W, and the installation of monolithic suspensions. The sensitivity should be improved by a factor 3–5 with respect to the Virgo design.

In a few years time, the second upgrade, called 'advanced Virgo', is planned. The goal of this upgrade is to improve the sensitivity reached by Virgo+ by another factor 10 over all the bandwidth.

5. Conclusion

During the year 2005, the Virgo detector was in a commissioning phase. Two commissioning runs, called C6 and C7, were performed during the summer, and the sensitivity reached during the C7 run was $h \sim 6 \times 10^{-22}$ at 300 Hz, allowing us to reach a horizon value above 1 Mpc for an optimally oriented NS–NS binary. After doing hardware injections during the runs, data analysis algorithms were tested for binary coalescences and bursts. Virgo reached a level of sensitivity which is very promising and should improve in the coming months. A science run is foreseen at the end of 2006 for a few months. Joint analysis investigation and scheduling started during the last year, in particular in a joint LSC–Virgo data analysis group for bursts and coalescing binaries.

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