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Status and perspectives of the Virgo gravitational wave detector

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Abstract. Virgo is designed to detect gravitational waves of both astrophysical and cosmological origin in the frequency range from a few Hz to a few kHz. After the end of the first science run, partially overlapped with the LIGO fifth science run, the detector underwent several upgrades to improve its sensitivity. The second Virgo science run started at the beginning of July 2009 in coincidence with LIGO. A further upgrade is planned at beginning of 2010 with the installation of new suspensions for the test masses and of new mirrors. This will lead to a considerable improvement in the sensitivity and represents an intermediate step toward the development of the advanced detectors.

1. Introduction

Virgo [1] is a 3km power recycled Michelson interferometer where each arm is a Fabry-Perot cavity. It is located close to Pisa (Italy) at the European Gravitational Observatory (EGO). The detector is sensitive to gravitational waves (GW) emitted by spinning neutron stars, coalescing binaries, supernovae and stochastic background of cosmological origin. The commissioning of the Virgo interferometer begun in 2003. These efforts led, in 2007, to the first scientific run VSR1 [2] in coincidence with LIGO (Laser Interferometer Gravitational-wave Observatory) [3]. After VSR1, during 2008 and half of 2009, the commissioning activity restarted and the interferometer underwent several upgrades to further improve its sensitivity. In July 2009, Virgo started its second science run (VSR2) in coincidence with the sixth science run (S6) of the two 4 km long LIGO interferometers L1 and H1 (located in Livingston Parish -Louisiana- and Hanford -Washington State- respectively). At the beginning of 2010, monolithic suspensions will be installed and all the test masses will be replaced. These upgrades will increase the NS-NS coalescing binaries horizon by a factor of 5.

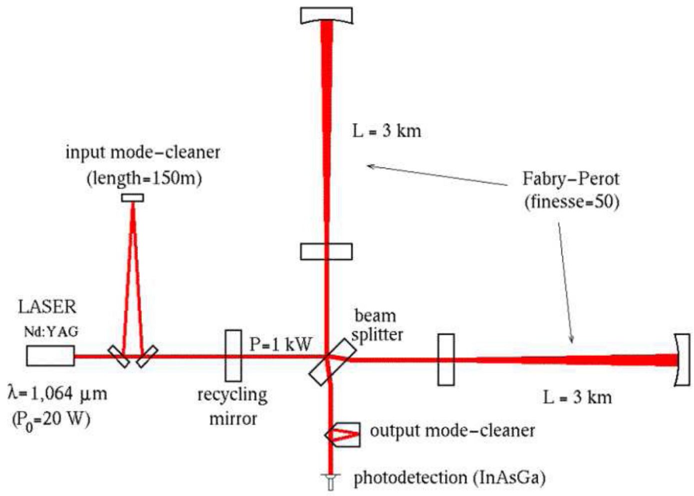

Figure 1. Virgo optical layout.

2. Virgo commissioning in 2008-2009 and the second science run

At the end of VSR1, in October 2007, an intense program of upgrades and commissioning started to lead the detector towards the Virgo+ configuration. Figure 1 shows the Virgo optical layout.

The main upgrades regarded the installation of a more powerful and less noisy read-out and control electronics, the installation of a laser amplifier that can deliver up to 25 W at the input of the interferometer and some upgrades of the injection bench, necessary to cope with the higher laser power and to provide a better seismic noise rejection. Moreover, a thermal compensation system (TCS) has been installed, to reduce thermal effects in the input mirrors. In fact, the absorption of a few ppm of the laser power on the input mirror coatings results in a decrease of the matching between the carrier and the sidebands, thus preventing lock acquisition at input powers above 14 W. TCS uses a CO_2 annular beam that heats the peripheral of the input test masses in order to flatten the optical path length inside the mirror substrates. The commissioning activity allowed to increase the input power from 8 W, used during VSR1, to 17 W at the beginning of the VSR2.

Thanks to these upgrades and the good outcome of the commissioning activity, the measured Virgo sensitivity is now very close to the design curve (see figure 2).

Due to the seismic attenuation performance of the Superattenuator [4], Virgo has a much better sensitivity than LIGO at frequencies below 40 Hz (three orders of magnitude better at 20 Hz). The difficulty to reach a good sensitivity at these low frequencies also depends on the presence of many technical noises (such as control noise, magnetic noise, diffused light noise). A good understanding of these noise sources has been reached, as shown again in figure 2: in fact the pink curve, that is the sum of all the known contributions, superposes very well with the experimental curve. A big effort is devoted to the understanding and reduction of the technical noise contributions. For example, a large fraction of the commissioning work has been devoted to the mitigation of diffused light. In fact, the optics located on the external benches can retro-diffuse light into the interferometer. Since these optics are not seismically isolated, the diffused light introduces phase noise that masks the gravitational wave signal. To reduce this noise, some activities have been performed: mitigation of environmental noise, acoustic isolation of the benches and improvement of the optical set-up.

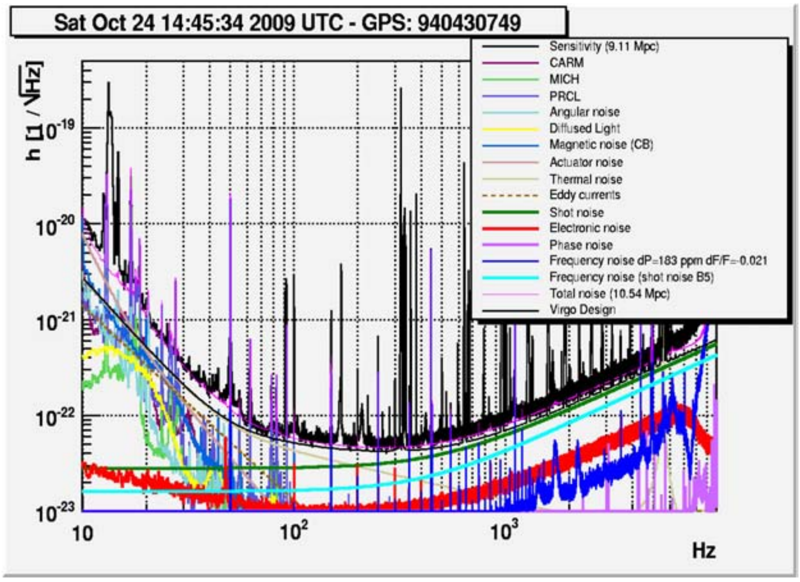

Figure 2. Noise budget: the black curve represents the measured sensitivity. The coloured curves show all the known and modelled noise sources and the thin purple curve is the sum of all these contributions.

All these actions led to an enhancement of the NS-NS averaged horizon from 4 Mpc in VSR1 to more than 9 Mpc during VSR2. After four months of run, the integrated science mode duty cycle is higher than 80%.

3. Virgo+

Virgo+ is a technologically enhanced configuration aimed at improving the detector sensitivity: in particular, when all the upgrades will be implemented, the averaged horizon distance for coalescing binary neutron star systems will increase from 9 to 45 Mpc, corresponding to a 2 orders of magnitude improvement in the observable volume. Both technical and fundamental noises, such as shot noise, mirror and suspension thermal noise, must be reduced.

Shot noise, affecting the high frequency part of the sensitivity, can be reduced by increasing the input power. The present laser amplifier can deliver up to 25 W, 30% more than during VSR2.

Low frequency sensitivity is limited by the thermal noise of the last stage of the suspension system, i.e. the pendulum to which the mirror is suspended. This noise is due to the friction between the mirror substrate and the suspension at the attachment point. The installation of monolithic suspensions will reduce this noise: the input test masses will be suspended with fused silica fibers instead of metallic wires. The technique for fibers production and selection is now well established and the robustness of the new set up has been checked.

The sensitivity around 100 Hz is limited by the mirror thermal noise. Thus, new mirrors with better substrates and coatings are being prepared. A further improvement of the sensitivity in this frequency range comes from the fact that the new test masses will allow to increase the arm cavity finesse from the present 50 to 150. The installation of monolithic suspensions and new test masses will take place at the beginning of 2010. Figure 3 shows the expected Virgo+ sensitivity (black curve) compared to the present one (red). A further reduction of technical noises (such as the beam jitter noise and the noise induced by the magnetic actuators on the test masses) will be necessary to reach the design sensitivity.

Besides representing a relevant scientific step thanks to the increase of sensitivity, these upgrades will give the unique opportunity to explore a region of lower noise before the construction of the advanced detectors (Advanced Virgo and Advanced LIGO) expected to enter in operation in 2014.

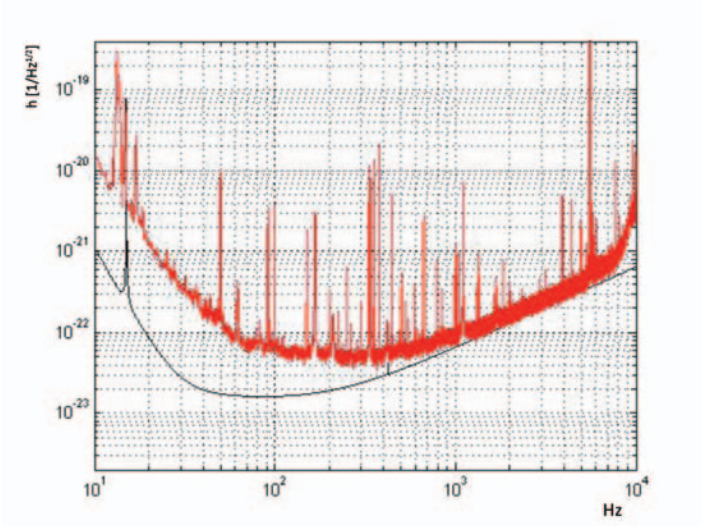

Figure 3. Virgo+ design sensitivity with monolithic suspensions (black), compared to the present sensitivity (red).

4. Conclusions

The Virgo detector is now running its second science run with a sensitivity close to design and a science mode duty cycle higher than 80%. NS-NS coalescing binaries horizon has increased by more than a factor of two with respect to VSR1. Early in 2010, monolithic suspensions and new test masses will be installed, completing the upgrade to Virgo+. The expected sensitivity corresponding to the Virgo+ design curve, expressed in terms of NS-NS coalescing binaries horizon should increase up to of a factor of 5 compared to the present one.

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