Noise budget and noise hunting in Virgo

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The actual sensitivity of Virgo is limited by technical noises: mainly control noises and environmental noises. Some recent commissioning activities aimed at the reduction of these noises are described in this paper and the present status of the noise budget is summarized.

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1 Introduction

Virgo [1] is a gravitationnal wave antenna based on a Michelson interferometer with 3 km long arms. In order to improve its sensitivity with respect to a simple Michelson interferometer, each arm contains a Fabry-Perot cavity and the power recycling technique is used [2].
The commissioning of Virgo started mid 2003 and the full interferometer was first locked in autumn 2004. In order to make possible the control [4] of the full interferometer the incident power had to be temporarily reduced by a factor 10. The final solution was implemented at the end of 2005 and the commissioning was restarted with the full power early in 2006. These activities and their impact on the sensitivity is summarized in Section 2. After a period of commissioning [3] with the increased power the interferometer was stable enough to allow some long data taking on weekends starting from september 2006 (the Weekend Science Runs: WSRs). Since then part of the commissioning activity was focused on the understanding of the noises limiting the Virgo sensitivity and on their reduction. These are mainly the noises introduced by the control loops (see Section 3) and environmental noises which couple to the dark fringe via diffused light or mirror position noise (see Section 4). The impact of these noises on the sensitivity is briefly described as well as the actions taken to reduce them since the first WSR. Section 5 summarizes the Virgo noise budget status and gives some perspectives.

2 Overview of recent commissioning activities and progress

Until september 2005 a problem of light retrodiffused by the input mode cleaner towards the interferometer prevented to reliably control the interferometer. To overcome this problem a temporary solution was adopted. This involved a reduction of the power incident on the interferometer by a factor 10. The final solution was the installation of a Faraday isolator between the input mode cleaner and the interferometer. This was implemented between september 2005 and january 2006. Other improvements were also made to the injection bench during this period. The power recycling mirror was also replaced with a larger one and its reflectivity was increased in order to increase the recycling gain.

These modifications were expected to give a significant reduction of the shot noise limit since the power was increased by a factor 10 and the recycling gain by 30%. Unfortuanetly the increase of the power revealed some thermal lensing effects: a small fraction (around 10 ppm) of the high power stored inside the Fabry-Perot cavities (about 4 kW) is absorbed by the input mirrors leading to thermal lensing effects and therefore to a distortion of the beam shape (mainly the sidebands). It was found that the lock acquisition could not survive this thermal transient if the power is too high. Therefore the input power had to be reduced by 25%. The final solution will be the implementation of a thermal compensation on the input mirrors.

Figure 1 shows the sensitivity measured before the shutdown (C7 run, September 2005) and after (WSR1 in September 2006 and WSR10 in March 2007). The improvement by about a factor 3 observed at high frequency (above 1 kHz) is directly related to the increased power incident on the Beam Splitter. During C7 run, below few 100 Hz the limiting sources of noise were control noises and environmental noises. During WSR1 the sensitivity was similar to the C7 sensitivity in this frequency band. Between WSR1 and WSR10 the controls have been improved and the environmental noise better understood and reduced. This results in the improvement in sensitivity shown on Figure 1.

3 Control noises

Since the mirrors are free at low frequency they need to be controled in order to keep the lenght of the cavities at the desired resonance conditions. A schematic view of the longitudinal control

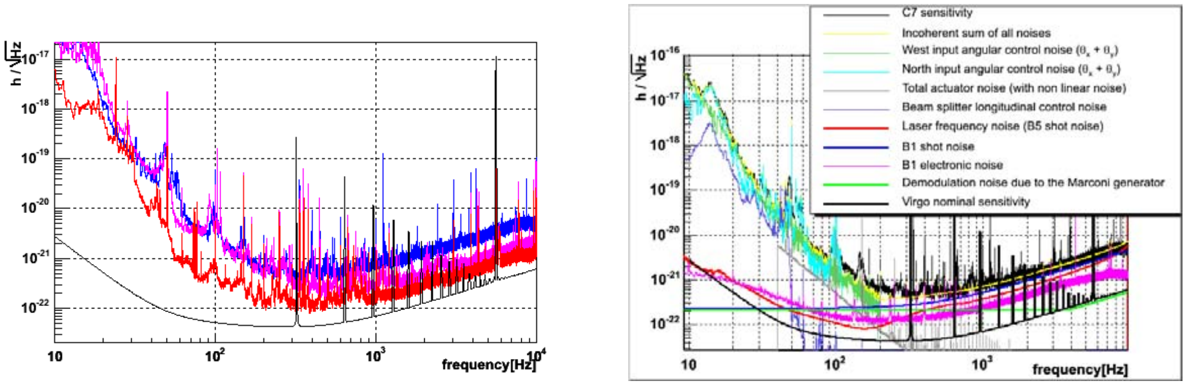

Figure 1: Left: comparison of the Virgo sensitivities during C7 run (September 2005, in blue), WSR1 (September 2006, in purple) and WSR10 (March 2007, in red). The Virgo design sensitivity is also shown in black. Right: noise budget during the C7 run: Virgo sensitivity (black) compared to all known noise contributions (colored curves).

is shown in Figure 4. These controls introduce, at higher frequencies, a position noise of the mirrors which is seen by the transmission port of the interferometer sensing the gravitationnal waves (denoted B1 on Figure 4 and refered to as dark fringe in the following).
Figure 1 shows the Virgo sensitivity curve (black) measured during C7 run and the contribution of known noises (colored curves). Up to about 150 Hz the sensitivity is limited by the noise introduced by the control of the mirrors. In this section the coupling of some of these noises to the dark fringe is explained as well as the actions which have been taken to reduce it. Details on the coupling of the control noises to the dark fringe can be found in[5].

3.1 Longitudinal control noise

The dominant longitudinal control noise arise from the control of the Beam Splitter mirror. This is due to the fact that any motion of the Beam Splitter is equivalent to a differential motion (up to a multiplicative factor) of the end mirrors as would do a gravitationnal wave.
Since this control noise is known and its coupling can be well modeled it can easily be subtracted on-line by moving the end mirrors in order to compensate for the Beam Splitter motion. This online subtraction was efficient to reduce the impact of this noise by a factor 10 during C7 and WSR1. Since then it has then been found that the coupling to the dark fringe was frequency dependent. Taking into acount this frequency dependence allowed to further reduce this noise by roughly a factor 2. This noise still limits the Virgo sensitivity below 40 Hz as can be seen in Figure 4. The on-line subtraction can slightly be improved but a better understanding and reduction of the noise source itself will be needed to reach the Virgo design sensitivity.

Another longitudinal control noise arise from the electronic noise of the mirror actuators. This noise limits the sensitivity around 60-100Hz (maroon curves in Figure 4). The impact of this noise can easily be reduced using shaping filters which allow to low-pass this noise.

3.2 Angular control noise

The rotation of the mirrors can be seen by the beam as a longitudinal motion of the mirror if the beam is not well centered on the mirror. The angular control noise couples then in a similar way as longitudinal control noise do. During C7 the angular control noise was limiting the sensitivity up to around 150 Hz. Since then several improvements have been done:

- the centering of the mirrors has been improved by roughly a factor 10

- the controled strategy has been improved, in particular special care has been taken to use more agressive filters for the control loops in order to avoid the reintroduction of noise in the Virgo frequency band.

Figure 2 shows the projection of the angular control noises to the dark fringe. These noises do not limit the present sensitivity. Some improvements will nevertheless have to be done in order to acheive the Virgo nominal sensitivity and will imply a reduction of the noise of the sensors (electronic noise, shot noise, ...).

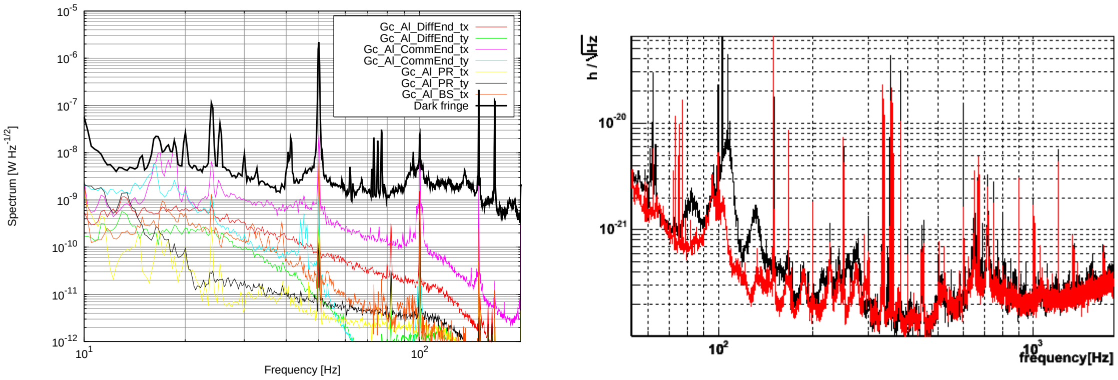

Figure 2: Left: Angular noise budget projected on the dark fringe and compared to the design sensitivity. Right: Virgo sensitivity during WSR7 (black) and WSR9 (red) runs: bumps from diffused light are visible during WSR7 and dissapeared after the improvement of the end optical benches.

3.3 Frequency noise

In a perfect interferometer the laser frequency noise should not couple to the dark fringe since it should cancel through the interference of the beams reflected by the Fabry-Perot cavities. However, since the two arms are not perfectly symmetric the cancelation is not perfect and it couples to the dark fringe through the asymmetry of finesse or losses of the Fabry-Perot cavities. Between WSR1 and WSR10 several improvements lead to a reduction of the frequency noise and of its coupling to the dark fringe as well:

- the electronics used to stabilize the laser frequency has been improved and the gain increased. This lead to a reduction of the frequency noise itself.

- the improvement of the angular control helped to reduce the coupling to the dark fringe: since misalignments increase the losses inside the Fabry-Perot cavities, it also increases the asymmetry between the cavities and therefore the coupling to the dark fringe.

- the matching of the beam to the cavities has also been improved also leading to a reduction of the coupling to the dark fringe.

After these improvements the frequency noise limits the Virgo sensitivity only in a small frequency band around 6kHz (shown with blue curve in Figure 4).

4 Environmental noises

Environmental noise (acoustic, seismic, magnetic) can couple to the dark fringe in ways which are difficult to predict and model. Environmental sensors (microphones, seismometers and magnetometers) located at several places around the interferometer are used in order to understand the path of these noises to these dark fringe. Some example of the investigations which have been performed as well as the actions taken to reduce the impact of these noises are given in this section.

4.1 Diffused light

Optics located on the external optical benches can retro-diffuse light into the interferometer due to, for example, the imperfections of their surface. Since these objects are not isolated from seismic noise the retro-diffused light carries some phase noise (proportionnal to the motion of the optic) which is equivalent to a de-phasing induced by a gravitationnal wave.

The main source of retro-diffused light has been found to arise from the external benches located after the end mirrors. A small fraction (40 ppm) of the power stored inside the Fabry-Perot cavities is transmitted by these mirrors an analysed on an optical bench.

During WSR7 run (January 2007) some non-stationary noise was observed in the dark fringe around 100 Hz and above. Some coherence with a photodiode signal and with a seismometer sensor located on this bench showed that the source could be diffused light. Some tests where performed on these benches in order to validate this hypothesis: this noise disappeared when the beam was dumped before the bench (i.e. not reaching the optics) while it increased when increasing the acoustic (and therefore seismic) noise around the bench. An improvement of the setup of the benches (more rigid mounts, larger optics,...) allowed to reduce the diffused light as can be seen in Figure 2 (right plot). In order to further reduce this noise an acoustic enclosure to be installed around the benches has been prepared.

4.2 Magnetic noise

After the reduction of diffused light other 'bumps' of noise showed up around 100 Hz. It was found that this noise was coherent with the magnetic noise measured by magnetometers located in the central area (see Figure 3). It was also shown that this noise was not coupled through the photodiodes electronics but was seen as a real motion of the mirrors. Since the longitudinal position of the mirrors is controlled with two magnets glued to the mirrors, a magnetic field can displace the mirrors. In order to avoid this effect the polarity of these two magnets is reversed with respect to eachother, except, by mistake, on the input mirrors. Sources of magnetic noise were therefore looked for around these mirrors. Some noisy power supplies showing the same noise structures around 100 Hz was found and the noise was well reduced when these were moved away from the mirrors (see Figure 3).

It is likely that some magnetic noise still limits the sensitivity in the frequency band 50 to 100 Hz and deeper investigations will be needed.

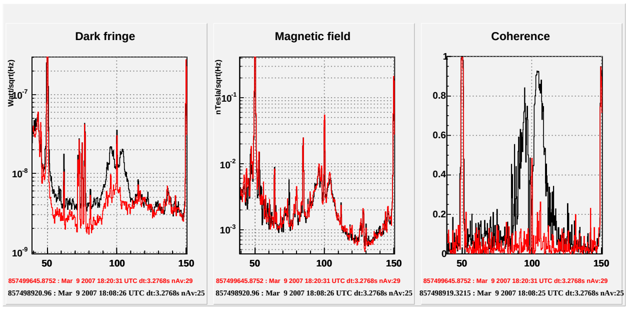

Figure 3: Left: Dark fringe spectrum (left) magnetic noise spectrum (middle) and coherence between these two signals (right), zoomed around 100 Hz. The black curves are with the noisy power supplies ON while the red is when these have been switched OFF.

5 Summary

The Virgo noise budget at the time of the conference (March 2007) is shown in Figure 4 where the measured sensitivity (black) is compared to the known noises. In the low frequency (below 100Hz) the sensitivity is limited by the longitudinal control noises, like the Beam Splitter mirror control (light green curve), but also by some unmodeled environmental noise which has been cured since then. As discussed in Section 3.2, the angular control noise does not limit the sensitivity. The control noises can be further reduced by improving the on-line subtraction technique or by using more agressive control filters or reducing the noise itself.
At high frequency the sensitivity is shot noise limited (dark green curve). The shot noise will be reduced when the thermal compensation will be installed and the laser power can be increased. In the intermediate frequency band (100 Hz to 1 kHz) some structures are observed above the shot noise, which are related to environmental noise. Some of these structures are expected to be cured with the acoustic enclosures to be installed around the optical benches, others still have to be understood.

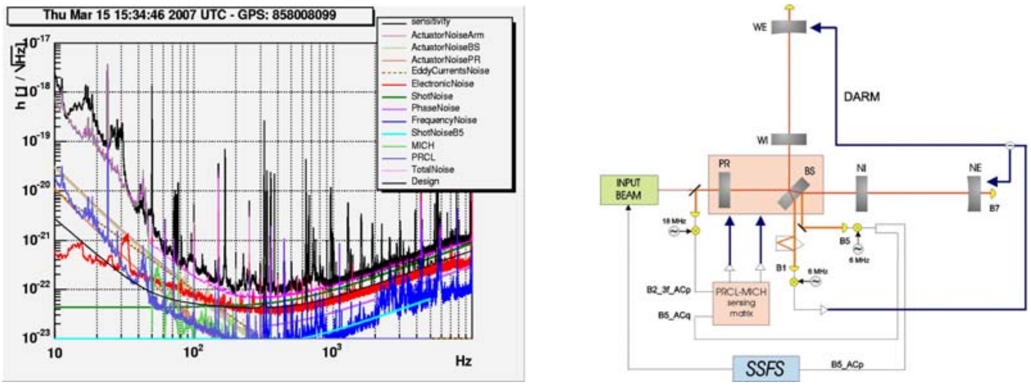

Figure 4: Left: Recent noise budget (mid March 2007) of Virgo. Right: Longitudinal control scheme of the Virgo interferometer.

References

1. The Virgo Collaboration, Final Design Report (1997) Virgo Technical Note VIR-TRE-DIR-1000-13.
2. R. W. P. Drever, in: T. Piran, N. Deruelle (Eds), Gravitational Radiation Proc, Les Houches Summer Institute, North-Holland, Amsterdam, 1982, p.321.
3. The Virgo Collaboration, *The status of Virgo*, in these proceedings.
4. The Virgo Collaboration, *The variable finesse locking scheme*, Class. Quantum Grav. **23**(2006)S85-S89.
5. R. Gouaty, *Analyse de la sensibilié du détecteur d'ondes gravitationnelles Virgo*, PhD thesis, Université de Savoie (2006).