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Environmental noise: experience with VIRGO/V+ commissioning and indications of further mitigation

I. Fiori – EGO

VIR-019B-09

(new release of VIR-019A-09)

April 16, 2009

VIRGO * A joint CNRS-INFN Project
Via E.Amaldi, I-56021 – S. Stefano a Macerata – 56021 Cascina, Italy
Secretariat: Telephone (39) 050 752 511 * FAX (39) 050 752 550 * e-mail virgo@ego-gw.it

Introduction

This document describes the major ITF noises of environmental origin evidenced (or, for a few cases, just suspected) during VIRGO commissioning and the first phase of V+ commissioning (until April 2009). For each noise the following information is provided: (1) a description of the noise observed in ITF and the noise path, (2) the source(s) of environmental disturbance, (3) applied remedies and results (possible side effects), (4) the residual noise and (5) proposed additional mitigation actions. In addition, for each noise are given links to reference documentation. A few figures aim to describe some relevant mitigation achievements and residual noises from major sources.
Four noise categories have been identified: (1) coupling of low frequency seismic noise of external benches, (2) environmental noise coupling through external optics, (3) noise coupling at vacuum tanks which addresses three cases: (i) optical links (ii) suspended optics, (iii) tube baffles, (4) magnetic noise. One section is dedicated to each.

List of Acronyms:

CB = Central Building
LL = Laser Laboratory
DL = Detection Laboratory
EIB = External Injection Bench
LB = Laser Bench
EDB = External Detection Bench
WEB = West External Bench
NEB = North External Bench
VSR1, VSR2 = Virgo Science Run 1 (May to Oct. 2007) and 2 (planned to start July 2009)
INJ = injection
DET = detection
HVAC = Heating, Ventilation and Air Conditioning

1. Noise from low frequency motion of external benches / Air conditioning

Post-VSR1 sensitivity was dominated below 100Hz by the effect of light diffused at external benches and back-scattered into the interferometer [1]. The examined benches are:

- External injection bench (EIB)
- Laser Bench (LB)
- External detection bench (EDB)
- North and West End benches (NEB and WEB)

EIB, EDB, NEWB and WEB were found to contribute significantly. The coupling of the noise is not linear and causes up-conversion [2,3]. The dominant effect is associated to the large

horizontal motion of benches in correspondence to the first mechanical mode of the legs (around 15Hz for all external benches) [4,5].
The bench motion is excited significantly (5 to 20 times) by the acoustic and seismic noise from the air conditioning. For the larges benches (terminal benches and EIB) the effect of acoustic noise (air pressure pushing on the bench top) seems to dominate (eLog 21608).
Figure 1 shows the acoustic noise produced by major HVAC machines: Central Building (CB) hall, Clean Rooms (CR), Mode Cleaner (MC) building, and West and North end buildings (NE and WE). Figure 2 shows the acoustic noise produced in the hall by the HVAC machine of WE building and the coherent seismic excitation of the bench top. In case of strong microseism (≈1-3% of time), the dominant effect is the up-conversion of the 300mHz sea peak in the observable bandwidth (up to 50Hz) [5] (see also eLog 21749, 21658).

The legs resonances of EIB also couple a significant amount of “direct” noise (to distinguish from up-conversion noise). To this noise contribute both beam jitter and sensing noise reintroduced by some alignment controls using photodiodes located on EIB. A projection indicates that this noise is presently limiting (April 2009) the sensitivity mainly around 40-50Hz (EIB legs vertical modes) and a bit at 16, 19 Hz (EIB legs horizontal modes). See a tentative noise projection in Figure 5-top.
Fans and engines of the Clean Rooms HVAC machine (around 20Hz) , and cooling fans of racks and vacuum pumps (around 45Hz) happen to match the frequency of the EIB mechanical modes and are amplified (x10) on bench top.

1.1 Solutions and Results

S1) Reduce fraction of diffused light on benches: proper dump of parasitic beams, cleaning and centering optics, identifying and replacing diffusing optic components [6]. Note that from theory we expect noise to reduce as the square root of the fraction of diffused light power [3].
R1) Noise coupling was reduced by a factor 2 to 6 (April 2008). After these actions up-conversion noise was no more limiting (May 2008 data).

S2) Reduced transmission of NE mirror (from 40ppm to 10ppm, as in V+MS design) and reduced transmission of multiple reflections from NE mirror back face (AR coating of NE mirror, new output window with AR coating and tilted). Note that from theory the noise from terminal benches scales proportionally to the end mirrors transmission.[3].
R2) Noise coupling for the NE bench reduced by about 10 times [5]. We expected a factor 4 reduction of the coupling to come from the reduced transmissibility; the additional measured reduction has to be attributed to the elimination of multiple beams.

S3) Improved attenuation of Faraday Isolator on SIB, and installation of PMC [5].
R3) Noise coupling for EIB reduced by at least 10 times (measured an upper limit).

S4) Slow down of Central hall air conditioning fans. The two fans (inlet and outlet) have been slowed down by about 25%. While instead overall the air flux into the CB hall did not change, because of the concomitant opening of one air valve inside the HVAC plenum.

R4) Both seismic and acoustic RMS noise below 50Hz (in the central hall volume and on the floor) reduced by approximately a factor two [7]. See Figure 3. We derive the indication that most of noise produced by HVAC machine in the hall is linked to the fans mechanical energy and not to the air velocity and flux in ducts.
Side-effect: a new seismic peak at 12Hz associated to the rotation velocity of the new (slower) engines. This seismic is intense on CB floor. It happens to match the EDB bench legs first mode and it is largely amplified (x100) on bench.

S5) Installation of more rigid Plexiglas cover box on NEB.
R5) This seems to have reduced the coupling of low frequency acoustic noise to bench and slightly reduced the amplitude of NEB mode (eLog 21115, 21198).

1.2 Residual noise

Figure 5-top summarizes projections of noise from low frequency motion of external benches, as of April 2009. The situation is the following:
(1) After actions S1, S2 and S3 the NEB and EIB projected noise are at least a factor 3 below V+ sensitivity (upper limit measured).
(2) The WEB noise is about a factor two above Virgo design around 20 Hz. In conditions of high microseism will produce limiting noise up to 40Hz (eLog 22377).
(3) Noise couplings at EDB and Detection tower are presently under study. We have evidenced that the CB hall air conditioning noise is contributing to limit present (April 2009) sensitivity at 20-100Hz. See Figure 4. The coupling path has not been yet identified, however coupling to EDB or Detection tower (via diffused light) is suspected [8].
(4) The EIB bench motion seems to couple significant noise, particularly around 40-50Hz, because of its large motion at the vertical bench mode.

1.3 Mitigation actions planned before VSR2

(1) Installation of one isolation stage (soft springs) underneath fans and engines of CB hall air conditioning. We expect to reduce sensibly seismic noise transmitted through floor above ≈ 10Hz.
(2) Reduction by 25% of fan speed and air flux of WE HVAC. Based on results obtained with the CB hall machine we would expect to reduce to about half the acoustic noise and seismic excitation of WEB bench at the first legs mode.
(3) Installation of more compact and rigid Plexiglas box on End Benches, which might reduce coupling of acoustic noise to benches.
(4) Improving acoustic isolation of HVAC room from WE experimental hall (work TBC). We suspect direct noise coupling plays a role, although we have never quantified it relatively to the acoustic noise associated to air fluxes. This work could shed light on this point.
(5) Dump beam B1s inside DET tower. This beam presently carries a relatively large amount of power on EDB, and is a possible source of back-scattering from EDB or from the DET output window.

(6) Better protect B1 beam path on EDB from dust and air fluxes.
(7) For EIB no specific action has been planned yet. The possibility to damp the bench motion at 40-45Hz by means of a mechanical damper is under study, as well the environmental sources which excite the bench mode.

1.4 Longer term mitigations

Figure 5-bottom shows a tentative projection of noise from benches for V+MS. The noise projection for diffused light looks not so critical but some reduction seems necessary to assure a safe margin. Possible actions are listed in points below. The noise coupling at EIB looks critical and a reduction of bench motion seems necessary, possibilities are listed in point 2 below. Some directives for AdV are also given.

1. **Reduce the amount of diffused light from external benches**, by the following actions: (i) for End benches: possibly further reduce transmission of end mirrors with respect to design (this choice has impact on ITF lock acquisition and controls and will have to be carefully evaluated); (ii) for EDB: assure a better cleaning of the bench, remove some beams from the bench; (iii) for EIB: further improve isolation of the input Faraday isolator (not really needed since EIB seems to couple very little diffused light).

2. **Seismic isolation of external benches.** A seismic isolation seems mainly needed for EIB. Some options being evaluated: (i) implementation of a controlled active isolation is certainly to pursue for AdV, but seems not feasible for V+MS given time and structural constraints (for example, tight volume of acoustic enclosures). (ii) Stiffening of the present bench legs structure has to be evaluated with simulation tools, in particular the consequence of possible increased bench motion at frequencies above 100Hz.

3. **Air conditioning noise mitigation.** We observe a large coupling of bench motion to acoustic noise, and we measure large acoustic noise emissions (0-100Hz) by the air conditioning machines (see Figures 1 and 2). This air-pressure noise seems to act directly on the bench, and it would so reduce the effectiveness of a seismic isolation of benches from ground. Therefore, a mitigation of acoustic noise seems necessary in all buildings. For V+MS we should proceed to slow down fans and reduce air fluxes in terminal buildings and Laser Laboratory (LL). From measurements of power consumption/heat dissipation it looks feasible to reduce significantly the air flux of the LL/Clean-rooms air conditioning [9]. At terminals, tests should be performed to determine precisely the temperature stability requirements of the SA and the external benches. The DAQ room and Clean Rooms air conditioning machines produce intense noise at engines and fans frequencies (<25Hz). It is advisable to reduce it by means of spring dampers.

4. **Benches cleanness.** Dust particle deposits on optics and crossing external beams cause significant amount of diffused light and glitches. This seems particularly critical for the External Detection Bench. Plastic covers can help to protect beams from dust particles and air fluxes. The implementation of a clean room environment in Detection laboratory should be considered for AdV.

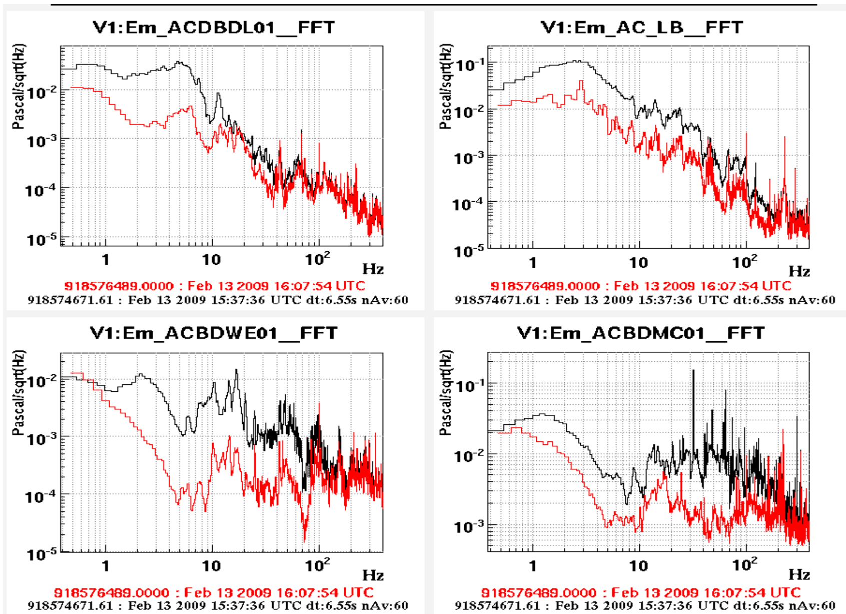


Figure 1. Acoustic noise reduction associated to the switch off of single HVAC machines (BLACK = machine ON, RED = machine OFF). The Upper left plot shows the acoustic noise from the CB hall HVAC measured by a microphone on EDB; Upper right plots shows the acoustic noise from the Clean Rooms HVAC measured inside Laser Bench enclosure; Bottom left is the acoustic noise contribution of the West end building HVAC measured by one microphone on WE bench; Bottom right plot is the acoustic noise of the MC HVAC measured in the MC hall.

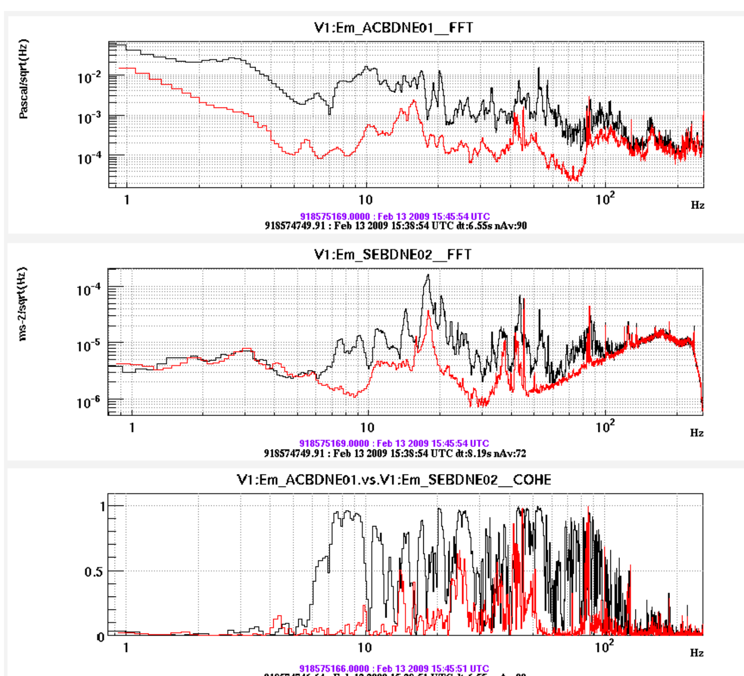


Figure 2. Noise reduction consequent to the switch-off of the WE hall air conditioning (black to red). TOP = acoustic noise, MIDDLE = seismic noise at WE bench top, BOTTOM=coherence of the two.

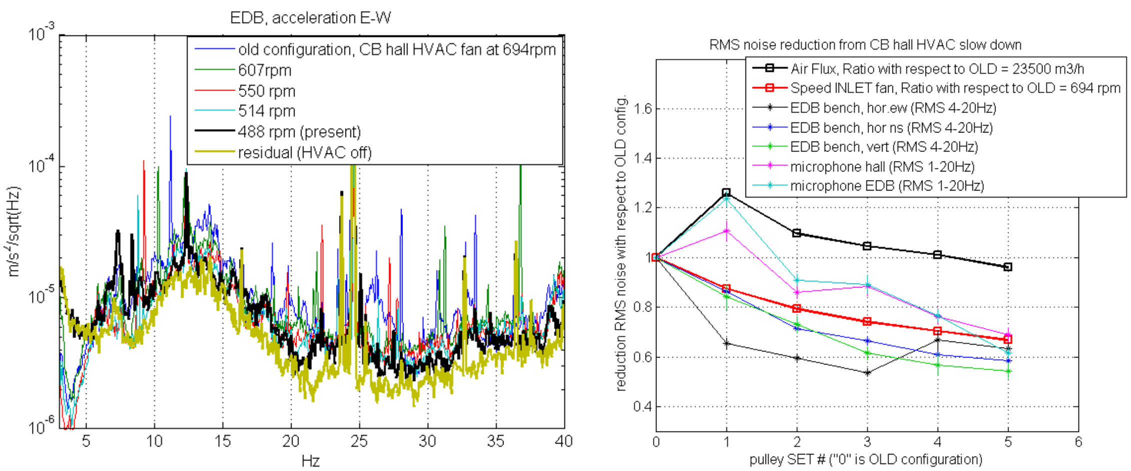


Figure 3. Measured reduction of a seismic noise (LEFT) on EDB consequent to the slow down of fans of the Central hall air conditioning. Residual noise is the difference of black and yellow curves. (RIGHT) RMS noise reduction of seismic and acoustic noise in CB hall and Detection, as function of the air flux and speed of HVAC inlet fan.

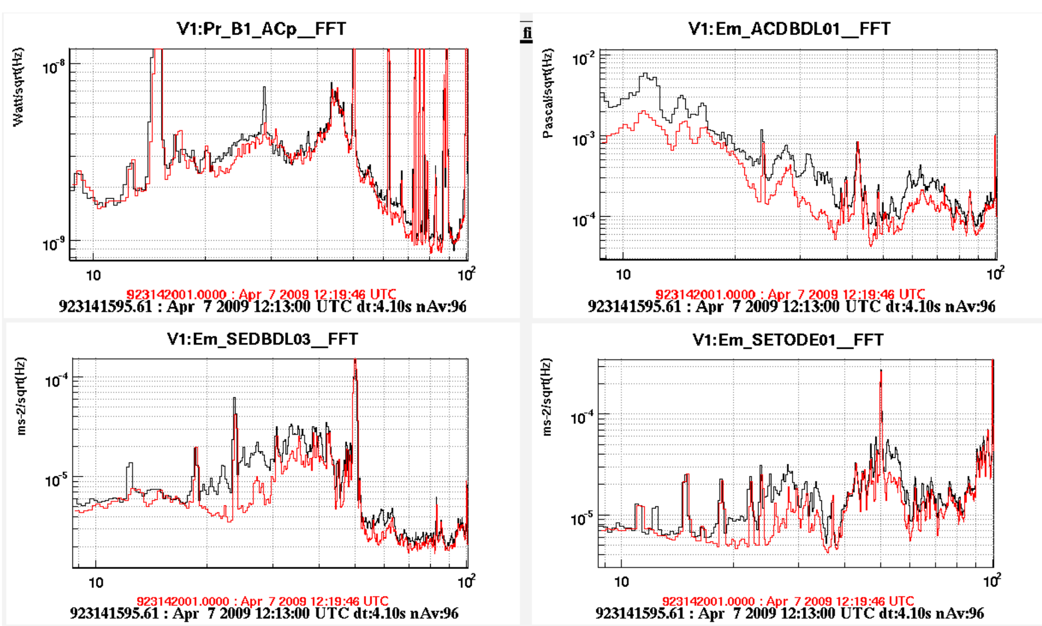
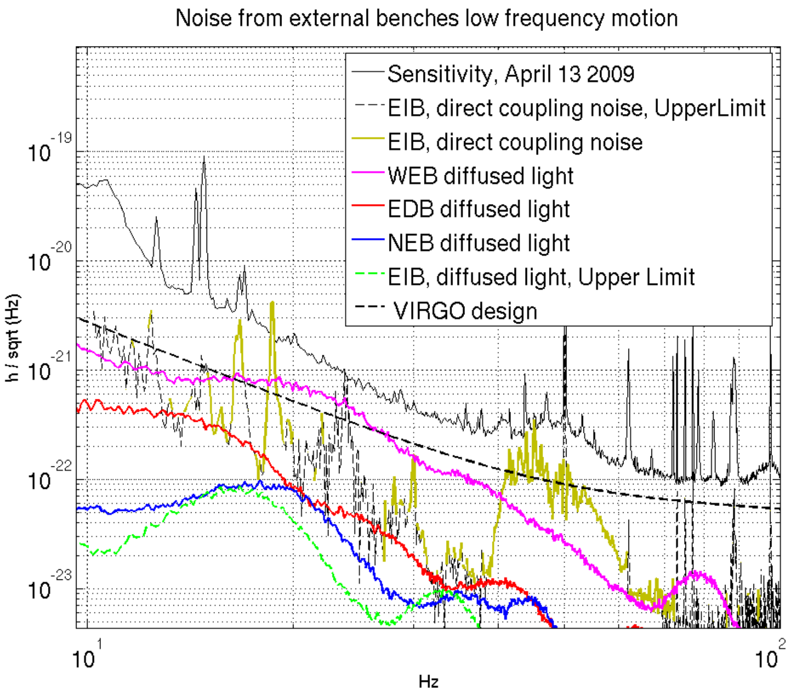


Figure 4. Effect of switching off the CB hall HVAC machine (April 2009): black curves correspond to the machine ON, red curves are with machine OFF. Upper left plot is the dark fringe, Upper right is the microphone on EDB, Bottom left is one seismometer on EDB and Bottom right is one seismometer on DET tower output window.



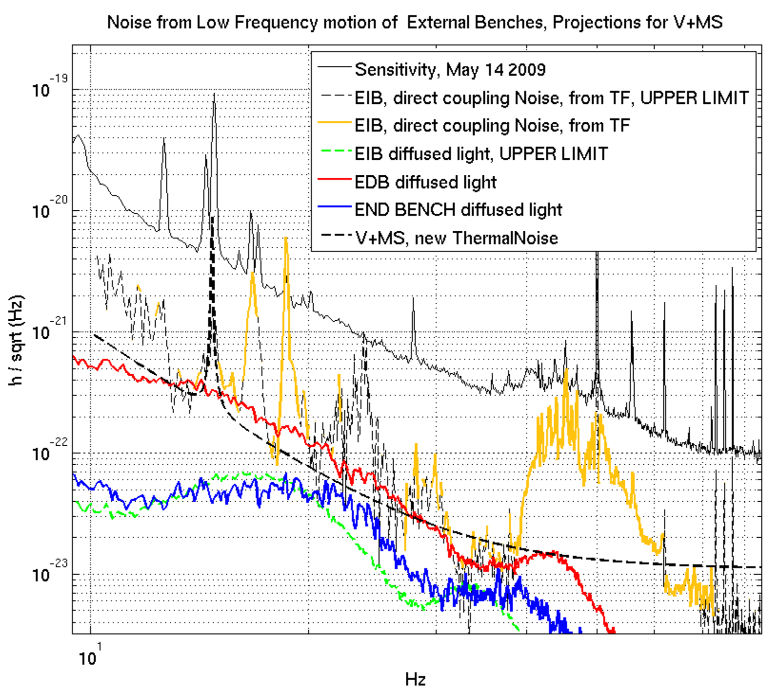


Figure 5. (TOP) Projection of environmental noise coupling through motion of external benches, as of April 2009. (RIGHT) Tentative projection of the same noises for V+MS.

2. Acoustic noise coupling to external optics / Racks cooling fans

Acoustic environmental noise couples to optics and beams on external benches. The three major mechanisms seems to be: (1) back-scattering of light diffused by optics whose motion is amplified at the resonant frequencies of the mounts by acoustic noise and seismic motion of the bench; (2) jitter of the beam caused by optics vibrations, and also by air refraction index fluctuations; (3) vibration of photodiodes placed on benches and used for alignment, coupling sensing noise in the control signals. Noise type (1) has been observed at all benches [1], while (2) and (3) seem most relevant at input benches [10], as also discussed in Section 1.
Cooling fans (of electronic racks and other devices) and pumps (vacuum, water pumps) are the major source of acoustic noise above 40 Hz. The noise evidenced in dark fringe are peaks associated to the frequency of optic mounts modes [11] and lines associated to racks cooling fans frequencies and multiples [4,12].
A related issue is that of noise caused by turbulent air fluxes on external beams. The observed effect is an increase of beam jitter noise below a few Hz (down to mHz).

2.1 Solutions and Results

S1) Several optic mounts replaced with stiffer ones (first resonance above ~300Hz).
R1) All peaks associated to optics on North external bench (NEB) disappeared from sensitivity [13]. New BMS mounts on the laser bench (LB) end the external injection bench (EIB) have resonances above 600Hz. Noise largely reduced on BMS above 50Hz [14].

S2) Acoustic isolation of benches: LB and EIB (26-27 Sept. 2006), external detection bench (EDB) (4-7 April 2007), and terminal benches (3-5 May 2007).
R2) The isolation performance measured for the terminal benches and detection are similar and slightly better than for the input benches. See Figure 6. For EIB and LB acoustic noise at benches reduces by a factor 2 to 5 above 100Hz [15], while for the terminal benches and detection bench we gained roughly a factor 2 at 50Hz, a factor 4 at 100Hz, and a factor 10-15 at 1kHz [13]. Seismic motion of benches reduced of a similar factor, indicating large coupling of bench motion to acoustic noise.
Limitations and side effects: Acoustic enclosures provide none or poor isolation below 100Hz. The EIB and LB enclosures do not provide good isolation from the CB experimental hall. A limitation in the design of LB and EIB enclosures is that of having left a too tight space around benches (this was improved in the other enclosures design).

S3) Racks relocation / EE-room isolation: racks in laser laboratory (LL) have been moved to acoustically isolated EE-room. Racks displaced by about 5 meters from LL inside EE-room. EE-room is separated from LL by two walls (MC tube runs between them): one is the original wall made of light panels; the second wall is made of acoustic isolation material. One acoustically isolated door separates EE-room from the central hall. At the same time the laser chiller has been moved from underneath the MC tube into a separate room with concrete walls.

A cooling system based on fan-coils has been adopted. Preliminary tests showed this to be much less noisy than a system like the one adopted for the DAQ room (see S3 in Section 3).
R3) Measured good acoustic isolation of LL benches (inside enclosures) from EE-room: SPL attenuation is a factor 100 at 100Hz and a factor 1000 at 1kHz [16]. See Figure 7. Acoustic noise in LL reduced above ~200 Hz. Effect on seismic noise yet to be verified after substitution of benches HF seismometers with less noisy ones. February 2009 data show no coherence between dark fringe and acoustic and seismic noise in EE-room.
Side effect: Observed over-heating of some laser electronic components is possibly related to a not good air circulation in room, which still needs improvement.

S4) Racks of terminal building moved out of bench floor.
The structural joint between the tower and bench floor and the building floor provides a seismic isolation of a factor 2-4 from 30Hz (eLog 21291).
R4) Saw no evidence of seismic noise reduction on benches. This indicates that the racks seismic noise couple at benches is mainly of acoustic origin.

S5) Cures for air turbulences:
(i) Installation of silenced openings in enclosures,
(ii) Plastic cover on benches or critical beam paths, seem to improve situation. It is yet to be done / improved for some benches. It is also aimed to protect from dust.
R5) Silenced openings on LL enclosures reduced LF beam-jitter noise almost to the level measured before the installation of enclosures. But still the problem reappears from time to time.

2.2 Residual noise

(1) The acoustic pollution from racks inside the experimental halls is large. Indeed some coherence of racks fans and dark fringe is found in recent data. See Figures 8 and 9.
(2) Some cooling fans (one rack) are still inside LL, this dominates acoustic noise in LL above 100Hz. Cooling fans of racks on platform around IB were seen in May data, coupling mostly acoustic.
(3) Recent data indicate that also input beam jitter noise is significant at some peaks (likely other optic mounts resonances) and it is not far from limiting between 150 and 600Hz.
(4) Recent tests indicate that output beams are very sensitive to turbulent air motion (eLog 22036).

2.3 Indication of further mitigations

(1) No mitigation actions are foreseen before VSR2, except possibly some stiffening of mounts on EIB.

(2) **A better isolation of LL from central hall** seems needed in near future. Racks cooling fans should be eliminated from LL. There might be technical difficulties in displacing the rack

hosting the Master Laser Power Supply. The noise from this rack should be verified, and alternative cooling solutions investigated.

(3) **Displacement of racks from the experimental halls.**
It seems necessary for the long term (AdV). This action is also motivated by noise couplings at output windows and tower walls, described in Section 3.
Our experience indicates that hosting racks in isolated rooms (like we did for EE-room) should be preferred to acoustic enclosures.
For the cooling of EE-rooms, fan-coils based systems seems a good choice from the point of view of noise, but the problem of air circulation has to be addressed.

(4) **Reduce reverberation time of experimental halls.**
The central building experimental hall has a measured reverberation time of the order of 3s. Reduce multiple sound reflections inside experimental halls would help reducing audible acoustic energy stored inside the halls volume and produced by racks, pumps, cooling fans. We expect, by installing appropriate phono-absorbing elements on the walls and ceilings to obtain a significant gain above ~100Hz.

(5) **Turbulent air fluxes.**
We have indications that air turbulences on external beams on EIB [13,14] and terminal benches (eLog 20076) and more recently on EDB (eLog 22036) produce noise on quadrant photodiodes used for alignment and in dark fringe. Short term action plan is to cover some beam paths on EIB and EDB. The problem should be better addressed for V+MS and AdV.

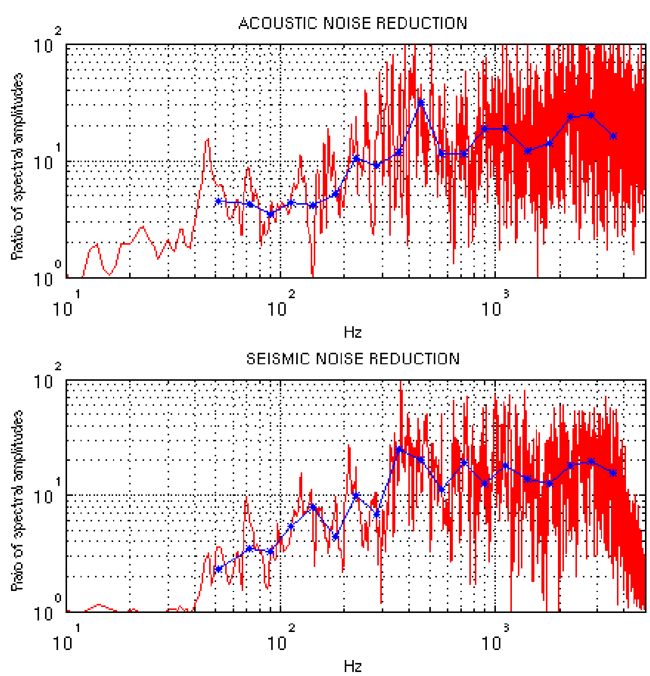


Figure 6. Acoustic and seismic noise attenuation of external detection bench provided by the acoustic shield of detection room.

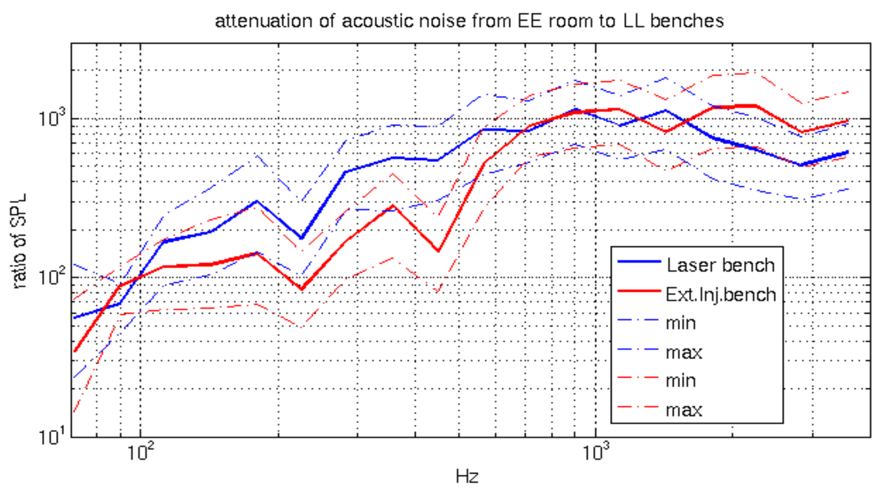


Figure 7. Acoustic noise attenuation between the EE-room and the laser benches (inside acoustic enclosure).

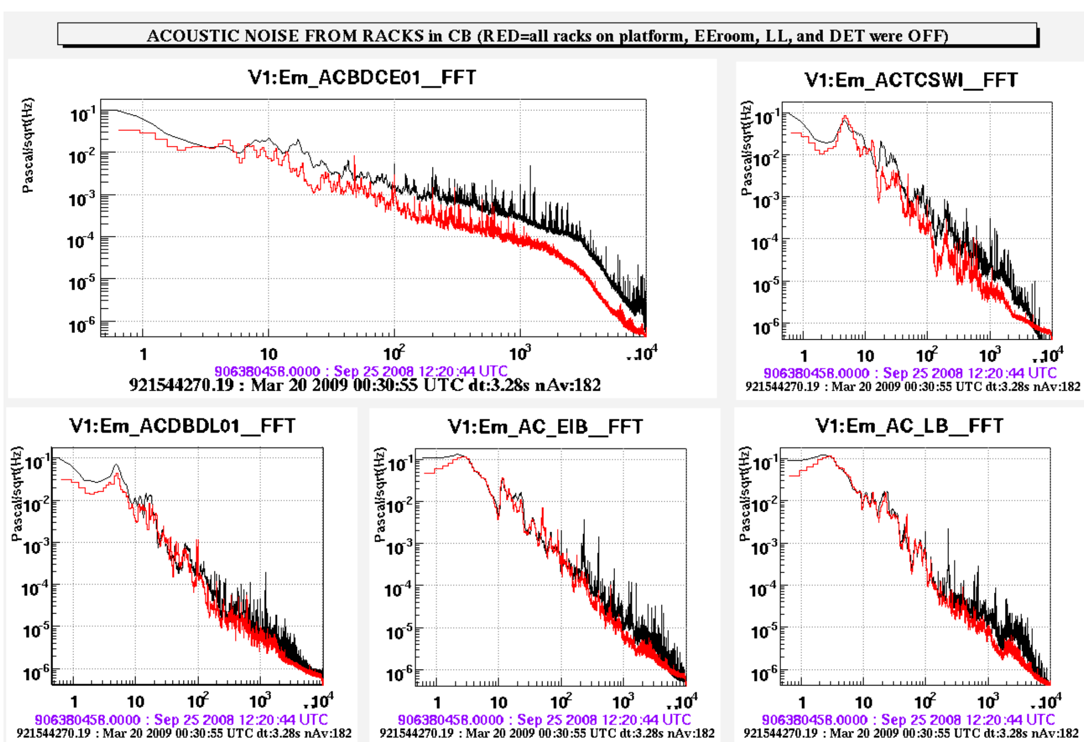


Figure 8. Acoustic noise produced by racks in the central experimental hall. Red curves correspond to all racks in LL, DET, and Central hall platform switched off. Some residual noise from DAQ room racks was present.

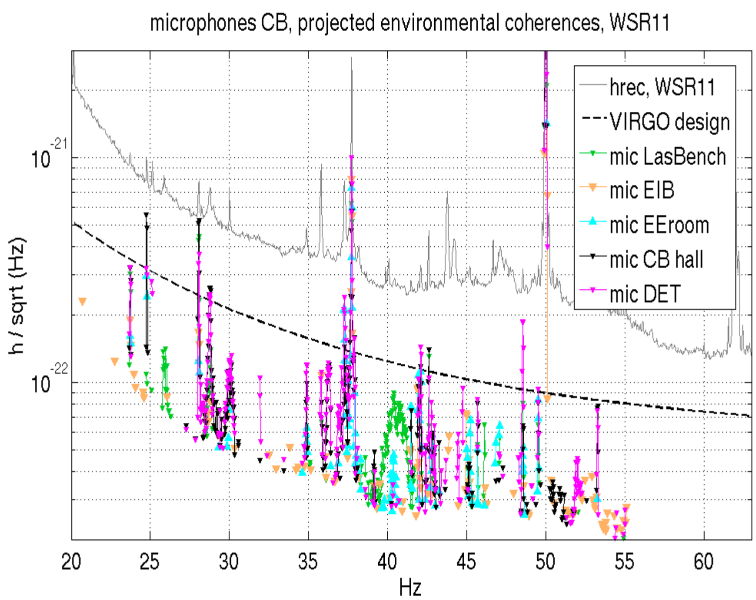


Figure 9. Projected coherence between dark fringe and microphones in the Central Building during WSR11 run (Feb. 2009). Measured coherences are multiplied by hrec and plotted. Some peaks have been identified associated to vacuum racks close to INJ. We suspect most of these peaks to be due to racks.

3. Noise couplings at vacuum vessels / Pumps, engines and fans.

This section describes the effects (measured or suspected) of vibrations of the vacuum vessels. In specific: the effects on optical windows (Sub-section 3.1), the effects on suspended benches (Sub-section 3.2), the effects on tubes and tube baffles (Sub-section 3.3). Vacuum vessels vibrations are excited both acoustically and seismically through the floor connection. Major environmental sources of noise are (i) vacuum pumps, (ii) rotating mechanical devices (water pumps, fans HVAC, racks cooling fans) and (iii) air conditioning engines and fans. Then, Sub-section 3.4 reports of residual noises, and Sub-section 3.5 lists suggested mitigation actions.

3.1 Optical windows

Noise effects in dark fringe had been evidenced or are suspected for: (i) Detection Brewster window [17], (ii) Detection output window [17], and (iii) Injection Brewster (eLog 22182).
Coupling mechanisms are not completely identified but suspected: (1) back scattered or back reflected light by the vibrating window, (2) modulation of the phase of the beam crossing the vibrating window (elasto-optical effects can change the index or refraction of the window), (3) clipping of beams.

The detection Brewster window coupled significant noise from 50Hz to some hundred Hz, especially picking up acoustic noise from the hall. Residual coupling noise after the Brewster removal was associated to the detection output window and it was mitigated by seismically isolating the turbo vacuum pump. Recent data indicate that noise coupling at this window and at the injection Brewster window could be not far from limiting the sensitivity at some frequencies between 30 and 400Hz (eLog 22162).

3.1.1 Solutions and Results

S1) Replaced Brewster window link before DET tower with cryogenic trap.
R1) Largely reduced acoustic coupling to central hall, some resonance peaks likely associated to Brewster structure disappeared. No evidence of residual noise or new type of noise produced by cryo-trap [17].

S2) Switch off of vacuum scroll-pumps. These pumps produce a loud acoustic noise at the pump frequency (24.5 Hz) and harmonics, and significant vibration of the towers, optical windows and benches. See Figure 10. Were found to affect significantly the sensitivity (first during run E7, and in more recent times: eLogs 19402 and 22554). Their continuous operation was found not necessary, and it has been limited to some short periods every 7 days or so.
R2) However, scrolls operation sometimes causes unlocks of SA inertial control, thus their seismic isolation is preferred. A first attempt to seismically isolate the pumps with rubber pads was not found effective. A more effective way might be that of suspending scroll pumps from the platform. This is presently under test by VAC group.

S3) Bellow installation on detection turbo pump. The pump was seismically isolated from the tower with the following installation: the pump is now hanged to a rigid support placed on a rubber isolating layer and attached to the platform, while the connection to the tower is made with a soft bellow steel tube (eLog 20166).
R3) Seismic noise to the tower is filtered significantly (factor 3 to 20) above 100Hz (also eLog 22196). The noise in dark fringe disappeared [17]. Residual seismic excitation of tower exists (mainly above 100Hz).

S4) Seismic isolation of water pump #1.
This pump (2-poles engine), located inside HVAC room, produces large acoustic and seismic noise at its rotation frequency (46Hz) and harmonics, which is heard in the hall and especially inside Detection lab. A soft rubber bellow was added downstream of the pump.
R4) This solution revealed not much effective to reduce noise in the hall. This might indicate that the disturbing noise emission is the acoustic component.
However, noise coupling to ITF reduced after Brewster removal, but a residual noise effect in dark fringe is detected in Feb. 2009 data. The pump is temporary kept off (not needed until hot summer time).

S5) DAQ room acoustic isolation. Acoustic noise from electronic racks in DAQ room, coupled to ITF via the Detection Brewster (in central hall, just outside of DAQ room).

R5) Acoustic noise in hall, just outside of DAQ room reduces approximately a factor 2 above 100Hz. Small but significant seismic noise reduction at Det. Brewster (few lines and peaks between 100 and 150Hz) [18].

S6) New DAQ room HVAC.
A new machine (providing about the same air flux ~5000 m3/hour) was moved outside the DAQ room. Fan and engines have been placed on rubber isolating layers, and the circulation of air under the DAQ room floating floor has been improved to assure a more uniform cooling of racks.
R6) Acoustic and seismic noise (floor) inside DAQ room reduced by about a factor 5 between 30 and 20Hz. Acoustic in the hall and seismic noise at EDB reduced a bit (factor 2-3) in the region 50-150Hz [19].
We find evidence of some noise in dark fringe in Feb. 2009 data. Intense seismic lines associated to new DAQ HVAC fans are measured on CB hall floor and EDB.

3.1.2 Further mitigation actions and investigations

For before VSR2:
(1) Isolating bellows on IB and PR turbo pumps (or substitution of IB turbo with MC turbo, now off, to be verified with test).
(2) Check for noise couplings at injection window.
(3) Improve DET output window (more polished, AR coated, larger wedge) to reduce back scattering (TBD).
After VSR2:
(1) A mitigation of DAQ room HVAC seismic noise seems (seismic isolation) seems needed.

3.2 Suspended optical benches

Environmental noise couples (1) because of light diffused by towers wall, (2) because of control noise of the angular alignment loops which act on suspended benches via coils attached to ground.
Point (2) is under investigation. Peaks associated to modes of the optics mounts on the suspended detection bench are seen in the sensitivity, indicating an excess motion of the bench. A suspect is that the excess noise is reintroduced by the mentioned coils actuators. This noise path is being investigated. A similar path is suspected for the suspended injection bench, being responsible for the excitation of some resonances of the dihedron on the bench which are found coherent with seismic sensors on ground and turbo pumps (eLog 22182).

3.2.1 Solutions and Results

S1) parasitic beams impinging of towers walls damped with suspended absorbing glasses, absorbing glass baffles to hide tube walls from beam, damping of parasitic beams on suspended benches [20].
R1) no clear indication of improvement. It is likely that some diffused light from suspended bench, and from secondary beams, remains. This light peaks up vibrations from tower walls, reintroducing phase noise.

3.3 Tubes and baffles

The noise coupling at tubes walls has been investigated for MC tube and the large arm tubes by shaking tests [21].

(1) For the large tubes an upper limit has been set for the noise that can be reintroduced by diffused light at the baffles. The limit is almost compliant with AdV design [22]. However, some hypotheses have been made which should be addressed possibly with further tests: (i) only the West tube has been tested, North tube might be different; (ii) not all baffles have been excited in the test, so set limit holds in the hypothesis that all baffles behave the same and there is no special baffle with defects; and (iii) also in the hypothesis that the environmental noise is the same on all baffles.

(2) Shakings tests of the MC tube permitted to set upper limits which are compliant with V+MS. Also it was found that the first section of MC tube, close to IB tower was sensitive to intense mechanical vibrations and shocks.
Therefore the following precaution action has been taken: the laser chiller, which was located right underneath the critical section of the tube MC, has been moved by a few meters inside a separate room with concrete walls.

3.4 Residual noise

Towers and pipes indeed are shaken significantly by several sources: (i) vacuum turbo pumps (Figure 11) significantly shake towers above 100Hz to kHz (in fact, so far, just the DET turbo pump has been damped with the bellow); (ii) the cooling fans of the turbo pumps at INJ and PR couple 45Hz seismic lines in dark fringe (eLog 20750); (iii) electronic racks produce noise above 20Hz that couple acoustically to towers and pipes (Figure 9); (iv) air conditioning fans and engines produce also significant ground vibrations below 100Hz (Figure 12).
Based on recent data (Feb. 2009) we suspect contributions of noise coupling at (i) the output DET window, (ii) the injection Brewster link, and (iii) at the DET and INJ tower base through ground coils. Also (iv) light diffused by inner tower walls of INJ and DET are likely but need further investigation.
In particular, the seismic noise from INJ and PR turbo pumps is found responsible of some residual peaks in dark fringe (eLog 22182) and also to have large effect on frequency noise (eLog 22116).

3.4.1 Short term mitigations

(1) Bellows on INJ and PR towers. The installation is planned before VSR2.

3.4.2 Indication of further mitigations

(1) **Isolation of all vacuum turbo-molecular pumps.** It has to be evaluated if a more performing bellow can be used.

(2) **Scroll pumps.** AdV requires the continuous operation of vacuum scroll pumps is necessary. However they can be placed at some distance (~10m) from the towers without compromising too much their performance. It is necessary to host them in a acoustically isolated room, and adopt a proper seismic isolation.

(3) **Remove cooling fans from experimental halls**. This means displace electronics racks whenever possible (see Section 1) and adopt an alternative cooling system (for example conductive type) for electronics that needs to stay close to towers.

(4) **Reduction of seismic and acoustic noise of engines** (also HVAC**) and water pumps** (recycling pumps for HVAC, compressed air pumps, and drain water pumps). The most effective action is, where possible, displacing the sources into acoustically isolated rooms. An effective seismic isolation might be achieved for fast engines and pumps using spring supports (i.e. under HVAC fans and engines) or suspending the pumps (i.e. vacuum scroll pumps needed for AdV).

(5) **Avoid engines frequency to match critical ITF resonances**. Difficult to say if better to use slow (8-poles) or fast (2-poles) engines: higher frequencies (i.e. 2-poles engines, around 50 Hz) are easier to damp (seismically) but lower frequency seismic and acoustic peaks (8-poles, around 12.5 Hz) are less relevant for sensitivity.

(6) **Eliminate alignment controls of suspended benches from ground coils.** Feasibility of controls acting from the marionette needs investigation.

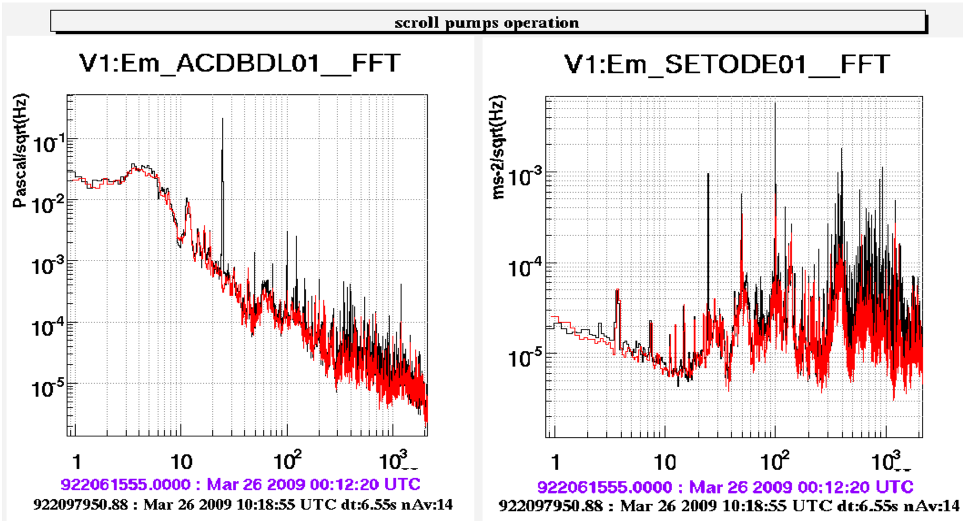


Figure 10. Acoustic and seismic noise produced by the vacuum scroll pump serving the DET tower. Black curves are with pump on, red curves with pump off. Left plot is a microphone on the EDB, right plot is a seismometer on the DET tower output window.

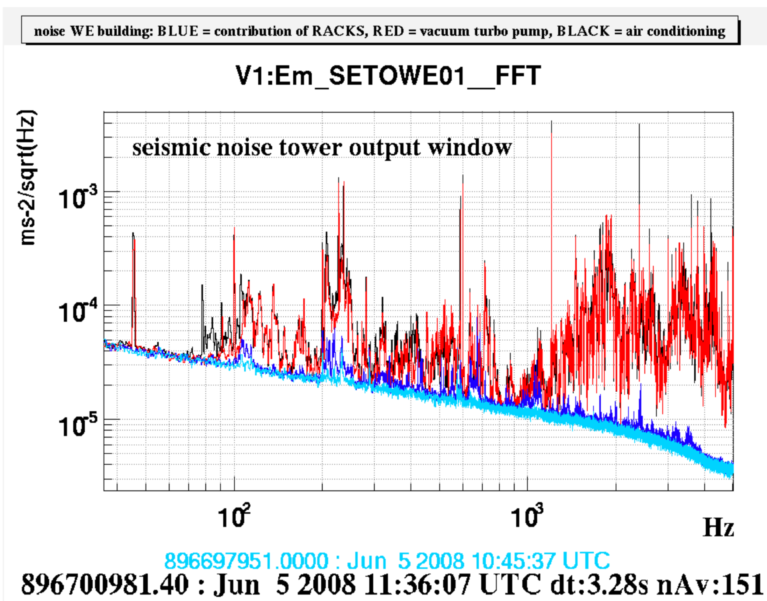


Figure 11. Seismic noise produced by the WE vacuum turbo-molecular pump measured at the tower output flange (red to blue). No bellow is installed on this pump. Also shown is the noise contribution from the air conditioning (black to red), and part of the contribution of the racks (blue to cyan). The cyan curve is essentially measuring sensor noise.

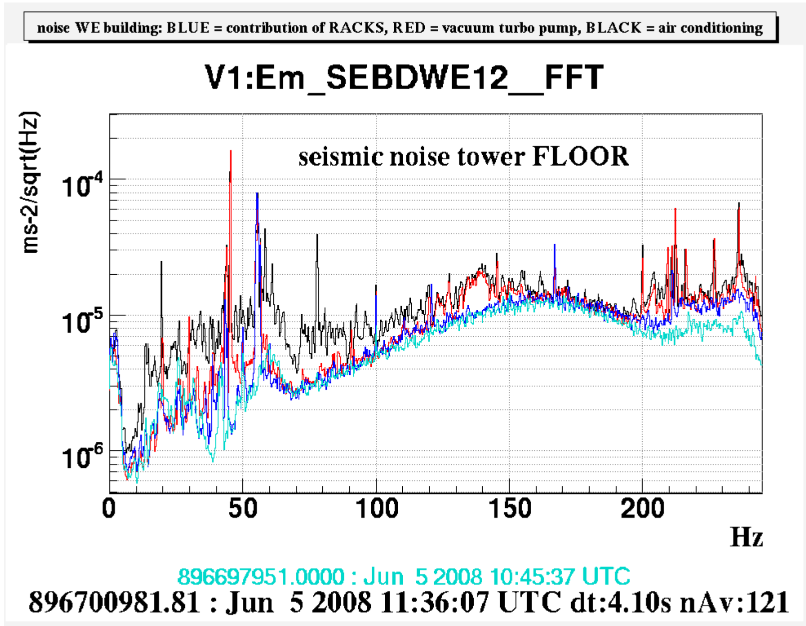


Figure 12. Seismic noise of WE hall floor produced by the air conditioning (black to red), the vacuum pump (red to blue) and the racks (blue to cyan). Measurements are partially limited by sensor noise.

4. Magnetic and RF noise / Various sources

Environmental magnetic fields produce noise in dark fringe through the force exerted on mirror magnets. Figure 13 shows a recent projection of this noise. The measured coupling to environmental magnetic fields decreases with a 3rd power of frequency and it is large below 50Hz [23]. Several actions have been taken to reduce this coupling (see item 1 below) and to reduce the effect of some magnetic sources (items 2, 3 and 9). Some other noise sources have been identified (items 4, 5, 6 and 7). We experienced some EM pollution of digital signals (see item 8).
Photodiodes signals can be polluted by radio frequency (RF) disturbances which fall within 20kHz from their modulation frequencies (6.26MHz, 8.35MHz, 14MHz, 22MHz). Sources of RF noise are being investigated in these days (see point 9 below).

4.1 Solutions and Results

(1) Mirrors magnets strength reduced, lateral magnets removed (April-May 2008)
Front mirror magnets on input and end mirrors have been replaced with ones of the same materials (SmCo) but smaller (5.68 times smaller magnetic moment). Also unused lateral

magnets have been removed (for WI and NE found they already dropped). This action was aimed also to reduce mirror thermal noise from induced Eddy currents in the reference mass.
Result of (1): Coupling to magnetic environmental fields reduced by about 5 times in CB. This seems mainly associated to the removal of NI lateral magnets [23]. Still to check improvement at WE and NE.

(2) Displacement of sources from ovens (March – November 2007)
Several power supplies located inside the ovens (<2 meters from payload mirrors) have been found responsible for bumps and lines in the sensitivity between 20 and 150 Hz [24]. These disappeared when sources where displaced by at least 5 meters from mirrors). Here a list of these sources: (1) vacuum sensors power supplies (eLog 15506), (2) power supplies of LC illuminator, (3) cooling fans of LC illuminator, (4) LC PSD power supplies, and (5) optical calibrators. Still a few, low emission apparatus are inside ovens: LC laser power supply, some electronics of PSD, LC cameras.

(3) Inductive loops in light circuits (July 2008)
Magnetic noise at and around 50Hz was associated to the switch on of fluorescent lights in the L-room. The source was identified in the large inductive loop associated to a wrong cabling of the in and return path of this light circuit. It was then cured by re-cabling it [23].

(4) MC resistive heating (July 2008)
Magnetic noise at sidebands of the 50Hz power line is present in the CB and couples to dark fringe [23]. The origin is the fast switching of the large resistive load (10kW) which is used for heating the MC conditioning air. This noise is still under study, but looks the path is through a pollution of the IPS power line, which is in common (same ENEL transformer) between the MC and CB.

(5) AC-DC power supplies of racks on platform (October 2008)
Large broadband magnetic noise emissions below 100Hz are associated to the AC to DC converters used by the vacuum controlling electronics (eLog 21327). These are hosted in vacuum and suspensions racks which are located at more or less 5m from suspended mirrors. We do not yet have evidence that this is the major source of LF magnetic noise coupling to the mirrors shown in Figure 13, although it is suspected. It is under investigation.

(6) Harmonic corrector
It was found to pollute the CB building UPS line with a broad 9kHz bump. The noise was present in several signals, including the dark fringe (eLog 17111, 17261). The noise path was not identified although coupling through ground loops is suspected. The excess noise seems related to the fact that the unit was overloaded, working at less than 10% of the maximum allowed load. The noise bump disappeared with the addition of a second unit working in parallel and sharing half of the load (eLog 20975).

(7) Noise from monitors, cameras
We detected in dark fringe the aliasing of one strong line at 15625Hz, which is the scanning frequency of TV monitors and cameras (eLog 22276). Although mitigations can be foreseen (shielding), the first mandatory cure seems improving data anti-aliasing filtering.

(8) EM disturbances from VME crates CPU
In two occasions we evidenced noise lines in dark fringe at multiple frequencies of some timing clock of VME crates CPU [24]. The suspected path is that the running process causes a periodic disturbance of crate power line which couples to non-differential ADC boards. The intensity of the noise seems related to the CPU load, and can become very large in case of some CPU malfunctioning. The noise was cured replacing some non-differential boards with differential ones, and restarting CPU (in the case of CPU malfunctioning).
Residual noise lines at multiples of 1 Hz, 10Hz and 2.36 Hz frequencies have been evidenced by pulsars analysis in VSR1 data [25]. In these days (February-March 2009) all ADC boards are being replaced with new differential ones. It has to be verified if this cure is sufficient.
Magnetic field emissions are measured at the noise lines, whose effect on analog electronic path has still to be investigated.

(9) RF noise from fluorescent lamps
Evidenced RF broadband noise (1-20MHz) generated from electronic circuit that drives some neon light tubes. It has been cured by replacing the driving circuit (eLog 21812, 21869).

(10) New electrical net (summer 2008)
The power line distribution (IPS and UPS) and the electrical grounding in central building have been renewed. The work was mainly motivated by safety (cure not CEE complaints) and by having a more rational and thus easier to maintain electrical net [26]. Some improvements have been made that ultimately might have reduced or prevented EM disturbances: (i) light circuits have been checked for inductive loops and cured (see 3), (ii) power cables paths are now further away from suspended mirrors and un-necessary cable loops around towers have been eliminated, (iii) the grounding connection of single racks has been checked and improved. In this contest, magnetic emissions from the main electrical panels, some of which are located at less than ~5m from suspended mirrors, have been measured and found to drop to negligible level at 1m distance.

4.1 Residual noise

(i) Recent data (Feb. 2009) and measurement of CB magnetic TF, indicate that magnetic noise is at level of the V+ design between 10 and 50Hz. Coupling at other buildings yet needs to be measured, although seems (from coherence studies) that their effect is less than for CB.
Residual limiting noise comes from the MC resistive heating and one magnetic line at 10.6Hz not yet identified.
(ii) A not yet identified disturbance is polluting dark fringe and some photodiode signals at few kHz. RF noise coupling to photodiodes demodulation signals is suspected (eLog 22338).
(iii) Analysis of WSR11-12 runs show residual pollution of 1Hz, 10Hz harmonics for which VME crates CPU and digital camera readout is suspected [27].

4.2 Further investigations

No evidence has been detected yet of noise produced by UPS machines. UPS machines serving the central and terminal buildings are located far from the experimental halls. The one serving the MC building is located inside the experimental hall. In the short term we foresee tests to evaluate the environmental noise emission of this machine, before planning the doubling of this machine which seems needed to reduce its load.

4.3 Further mitigations

(1) For the short term (VSR2, TBC) it would be advisable to shield or replace some vacuum racks AC/DC transformers (displacement is not feasible in the short term).
(2) The only solution for the 50Hz sidebands noise seems to be the replacement of the switching resistive load in the MC HVAC with a water-based heating, which means actually substituting the HVAC machine.
(3) For V+MS and AdV, the magnetic noise coupling should decrease with the installation of the dielectric reference masses (RM). In fact we evidenced that a large coupling is associated to the strong field gradients produced close to the mirror magnets by induced Eddy currents in the aluminum reference mass (see [23], and eLog 19988). However, it is not possible to predict which the residual magnetic coupling with dielectric RM will be.
It is thus advised a mitigation of magnetic noise sources to accomplish in the V+MS shut-down period. Noisiest identified sources are racks power supplies. The most effective action is the displacement of electronic racks from mirrors. Even a small displacement (5-10m) could be effective, since the radiated noise decreases as the cube of the distance from the source.

4.4 Other indications

(i) Avoid large fast switching loads.
(ii) The measured EM field emissions from crates CPU (see point 8 above) suggests the need to separate and keep at sufficient distance the crates CPU, ADC and digital signals paths from the analog signals paths.
(iii) Carefully evaluate use of fluorescent lamps, and checkup for RF emissions.
(iv) Useful to monitor EM fields close to mirror magnets with suited vacuum compatible permanent probes.
(v) Extensive use of differential transmitters (i.e. photodiodes) and receivers (i.e ADC) to minimize disturbance pick up from ground loops.

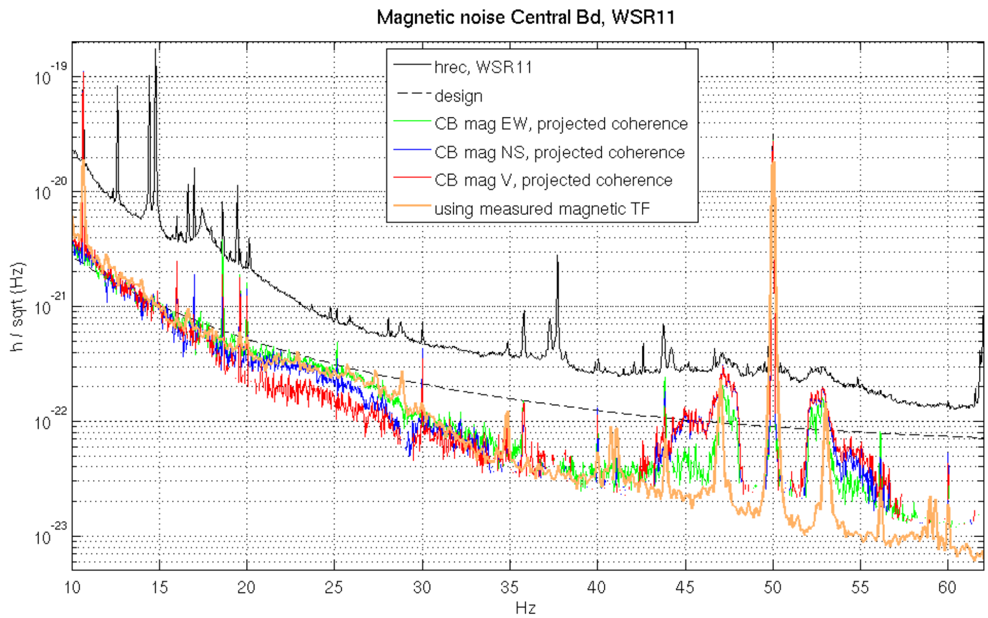


Figure 13. Projection of magnetic environmental noise coupling to mirror magnets in the central experimental hall. WSR11 data. The noise around 50Hz is due to the switching heating resistance of the MC building HVAC, as explained in Sec. 4.1 item (4).

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