Measurement of magnetic stray fields of voltage converters of the Vacuum equipment

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1. Introduction

Previous measurements [1] indicated that "Vacuum racks" (racks hosting the Virgo vacuum electronic equipment) "as a whole" produce relevant stray magnetic fields which might be of concern because of the coupling to actuator magnets used in AdV test masse [2]. In addition, comparative measurements [3] showed that among various rack components, power supply units are the most intense magnetic sources.

The present report aims at completing the work with the goal of characterizing individually each power module contained in the Vacuum racks. These measurements led to single out the most critical element(s) and eventually they could potentially be used to look for possible candidates for their substitution that do not present the same side effects.

In this note: Section 2 illustrates the test setup and measurement plan which includes: (1) comparison of stray magnetic field emission of single modules, (2) comparison with a "modified module" in which the built-in transformer is replaced with an equivalent toroidal transformer, (3) magnetic noise emission is put in relation with voltage noise of the mains, (4) test-bench measurements of magnetic stray fields from single modules are compared with measurements at one Tower Rack (North Input Tower Rack). Section 3 illustrates results. In Section 4 we conclude suggesting possible course of action to reduce magnetic noise emission of power supply modules.

Figure 1a. Tower Vacuum Rack.

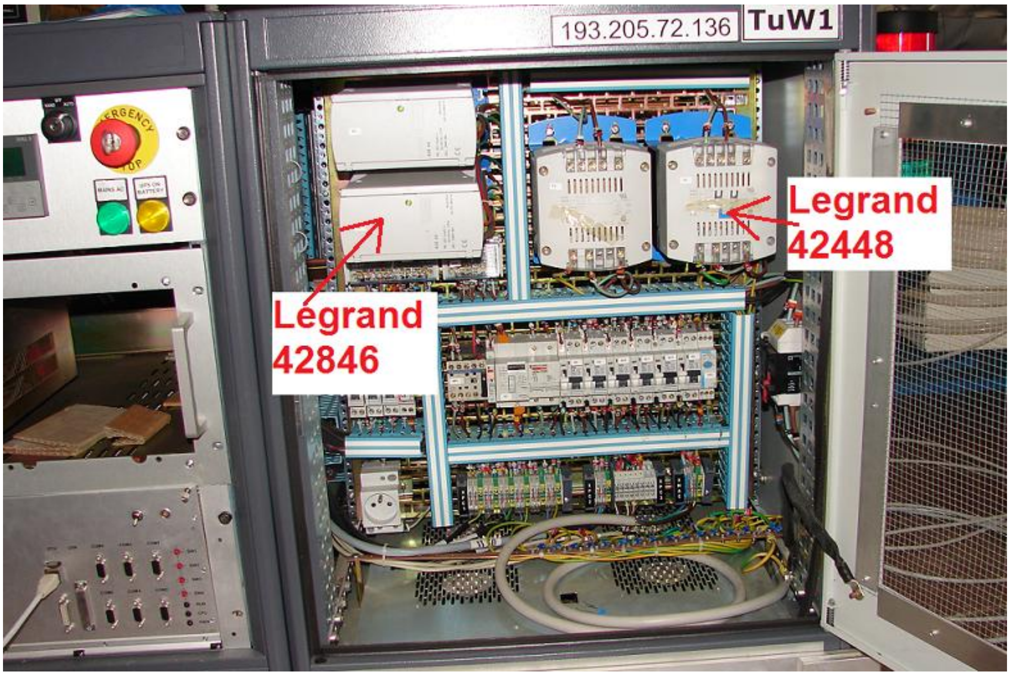


Figure 1b: **Vacuum Pumping Station Rack**

2. Measurements

2.1 Modules to be tested

Virgo Vacuum electronics racks contain two kinds of power supply "units", each using a series of commercial modules having different role, uses, characteristics and noise behaviors.

There are two kinds of "Vacuum Racks", one used for suspension towers and one for pumping stations along pipes.

The "Tower Racks" have a power supply section that includes the following modules (Figure 1 – TOP):

- ***Legrand* – 46923**: filtered rectifier power supply, 24V - 5A, 1 module per rack.
  This module is a classical AC-DC converter consisting in a transformer, followed by a diode rectifier and a low-pass filter to limit output ripples (Figure 3).

- ***Legrand* – 42468**: control and circuit isolation transformer, 630VA, 1 module per rack.

- ***TRACO* - TIS 300-124**: switching power supply 24V -12A, 1 module per rack.

The "Pumping Station" power units are made instead of the following modules (Figure 1 - BOTTOM):

- ***Legrand* – 42846**: filtered switching rectified power supply, 24V - 5A, 2 modules per unit. This module is similar to *the 46923*, but uses a switching mode voltage regulator.

- ***Legrand* – 42446**: control and circuit isolation transformer, 400 VA, 2 modules per unit. This module is similar to *the – 42468*.

We measured one spare unit for each of the above mentioned modules. In Table 1 we list measured output currents of working modules for various Tower Racks.

Module	Where	Module output Current, I (A)
L-46923	NI, PR, BS, DT, SR	650mA on NI, all other <50mA (*)
L-42468	NI, PR, BS, DT, SR	All <50mA
TRACO	NI, PR, BS, DT, SR	1.6A, 1.3A, 1.2A, <50mA, <50mA

Table 1: Output currents measured in working Tower Rack modules. (*) All racks were running in standard condition.

2.2 Measurement plan

Our first goal is to measure and compare the intensity of the stray magnetic vector field generated by each device under test. We used one tri-axis magnetic probe that we kept at a fixed position at a fixed distance from the module geometric center. We chose a distance of 0.5m in order to be able for all modules to measure the module emitted magnetic field exceeding the background magnetic field present when the module is off.

Transformers are known to vibrate at twice the AC power line frequency (50Hz in Italy) and multiples because of the magneto-striction effect of their ferromagnetic core. We attempt a comparative measurement of vibration noise of the units under test. With this goal in mind, we used one mono-axial piezoelectric accelerometer (Piezotronics, PBC393-B31 having DC to 300Hz bandwidth, and 10V/g sensitivity). We placed the seismometer in a fixed position at 0.5m from the module, deployed onto the same concrete slab on which also modules to be tested are placed. This way the seismometer measures the vibrations emitted by the modules to be tested and transmitted through the common concrete basement. Results were however not conclusive as explained in Section 3.1.

Stray magnetic fields arise because in a real transformer a small portion of the flux generated by the primary winding miss to couple the secondary windings and disperse in air. Stray magnetic field intensity might depend of various factors including, windings packing, core material's magnetic permeability and the core geometry. In a toroidal core transformer primary and secondary windings are wounded around a common donut-like shaped core. This type of transformers are said to have lesser dispersed magnetic flux with respect to other core geometries. We put this assertion under test, and we replaced the original transformer in the ***Legrand* – 46923** module with an equivalent (i.e. having the same output power) toroidal core (*MULTICOMP, Farnel part no. 306-8924, 24V -10A*, Figure 4), and made comparative measurements. Results are described in Section 3.2.1. We note that, toroidal core transformers are also said to have larger vibration noise with respect to other transformer geometries: in Section 3.1 we attempted to put this under test.

Since it is possible that the emitted magnetic vector field is not isotropic, i.e. the intensity varies with the direction, we repeated the measurement for different orientations of the module with respect to the probe: we kept the probe fixed and rotate the module along its main axis. Results are described in Section 3.2.2.

It is possible that the emitted magnetic field depends on the electric current supplied to the load by the module under test. Thus, we repeated measurements for different values of the output current, which we obtain by changing the module output load. We used exclusively resistive loads. We changed the output current within a factor about 3 of the current measured on working modules (details on loads and currents are given in Table 2). Results are described in Section 3.2.3.

Previous measurements [4] indicated that intensity of power modules grows proportionally with the amplitude of voltage noise of the power supply. In order to verify this, we measured and compared the magnetic field when one ***Legrand* – 42468** module is powered with the IPS mains first and then through the (noisier) UPS mains. Results are described in Section 3.2.4

Finally, in order to check the consistency of our measurements we compared the stray magnetic field measured on single modules in the test setup with that measured at a reference distance from one real assembled tower rack. Since other surrounding magnetic sources (racks) were switched off, we used the chance to measure how the magnetic field from this rack decreased with distance. This is described in Section 3.3.

1.1 Experimental set-up

Measurements need a low magnetic background field. We choose one outdoor location, in the little square garden of the EGO office building (a.k.a. "the Olive Garden"). The residual magnetic field intensity is the black-colored curve in Figure 7.

A sketch of the test setup is shown in Figure 2.

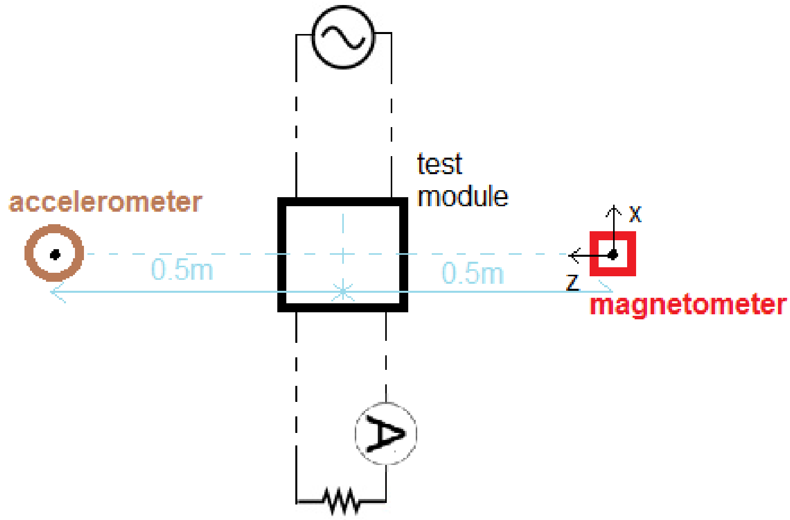


Figure 2: Schematic drawing of experimental the setup, top view.

For all tests:

- All modules were powered through a UPS outlet (230V-50Hz AC) in the EGO Electronics Lab. This outlet is served by one UPS generator, 20kVA by Riello (mod. MST 20 T1). For the UPS/IPS test mentioned above the IPS plug in the same Lab is used (see Section 3 for details).
- All test modules are in turn placed in the same position on a concrete slab (doorstep), at 0.5m distance from the magnetometer and from the seismometer also deployed on the same slab. Both the magnetometer and the seismometer are kept in the same position for all measurements, at 0.5m from the module center. Seismic probe is oriented vertically. Magnetic probe axes are oriented in this way: “Z” is horizontal and points towards the object, “Y” is vertical pointing up-wards, and “X” is horizontal and forms with “Z” and “Y” an orthogonal left-handed tern (see Figure 2).
- Intensity of three components of the magnetic field is measured using one 3-axis flux-gate magnetic field sensor: Mayer instruments FL3-100 (range ±100 μT, DC to 2 kHz. Sensitivity 10 V/ 100 μT, intrinsic noise at 10Hz ≈5pT for each single axis). The magnetometer is powered with the same electric outlet used for the load but we paid attention to place its small switching supply at least 3m away from the probe itself.
- Magnetometer signals are sent to a FFT analyzer (Ono-sokki’s CF-3650). The power spectrum of each on the three components is computed from 0.1Hz to 1000Hz with 0.15Hz resolution. During measurements, the FFT analyzer is powered using its back-up batteries.
- The module under test supplies power to a resistive load. In case of modules with DC output we used 47 Ω (1%, 15 Watt) resistors mounted on a slab of aluminum to ease power dissipation. Resistors in different series or parallel configuration were used to change the total load and thus the output current (see Table 2). Isolation transformers (230V AC output) need high-power resistive loads. We used illuminating filament lamps (60W and 15W) and a heating gun (variable current, 1500W max) as specified in Table 2.
- The module output current is measured. For DC currents we used a Tektronix-TX3’s probe (Voltage DC reading accuracy ±0.05%). For AC currents we used a LEM’s current probe based on Hall’s effect technology (LEM PR200, current range 20A AC-rms, bandwidth from DC to

10kHz, overall accuracy ±1% of reading or ±30mA, sensitivity 10mV/A). The current probe output was in turn read using the Tektronix TX3's probe (set to DC Voltage reading). We noticed the current probe needs a careful installation. In order to measure the module output current we clamped the probe jaws around one of the output wire of the isolation transformer module. We noticed the probe reading was disturbed by stray magnetic fields from the transformer module. Thus, we cared taking all current readings in a position along the output wire at about 1m from the module.

- The useful information is not the actual vector field orientation but its intensity ([1]). Therefore, in the following we combine the single magnetic field orthogonal components (B_x, B_y and B_z) measured by the probe into the vector modulus, defined as: $B = \sqrt{(B_x^2,B_y^2+B_z^2)}$.

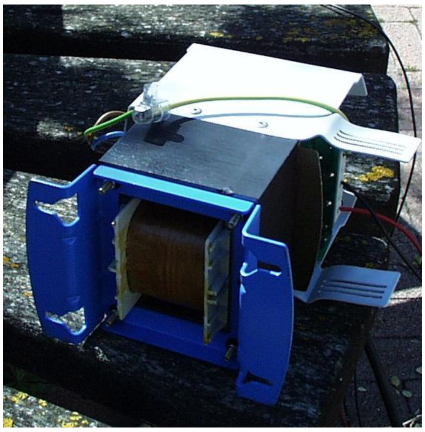
1.2 Measurements

Table 2 below describes our measurements and specifies the load and output current.

Module	Resistive Loads	Module orientations	Module output Current, I out
L-46923 (24V, 5A)	DC, (47+47)Ω	3 orientations	300mA
	DC, (47+47+47+47)Ω	1 orientation	150mA
	DC, 47 Ω	1	587mA
L-46923 modified with toroidal transformer	DC, 47 Ω	3 orientations	696 mA (*)
	DC, (47+47)Ω	1	350mA (*)
	DC, (47+47+47+47)Ω	1	178mA (*)
L-42846 (AC-DC 24V)	DC, (22 || 22)Ω	3 orientations	2.1 A
L-42468 (230V AC-AC)	AC, 60W lamp	3 orientations	240mA
	AC, 15W lamp	1	40mA
	AC, heating gun	1	765mA
	No load	1	0 (330mA on primary)
L-42448 (230V AC-AC)	No load	1 orientation	0
	AC, 60W lamp	1	240mA
	AC, 15W lamp	1	40mA
	AC, heating gun	1	760mA
TRACO (AC-DC 24V)	DC, 47 Ω	3 orientations	508 mA
	DC, (39||39) Ω	1	1.2 A
	DC, (22||22) Ω	1	2.1 A

TABLE 2: Tested configurations for each module. (*) The output voltage rms of the used toroidal transformer was 24V. Given the typical voltage conversion ratio of a full-wave rectifier (Vout=sqrt(2)*Vin) we expect the DC voltage output of the rectifier unit to be ≈33V (we indeed measured a 33V DC voltage at the "modified" L-46923 module). This explains why in the case of "modified" L-46923 we measured output current about 15% larger than for the "as is" L-46923.

[1] The actual orientation of Vacuum Racks power supplies it is not known a priori, and so the orientation of the stray magnetic field produced at the Virgo sensitive receptors.



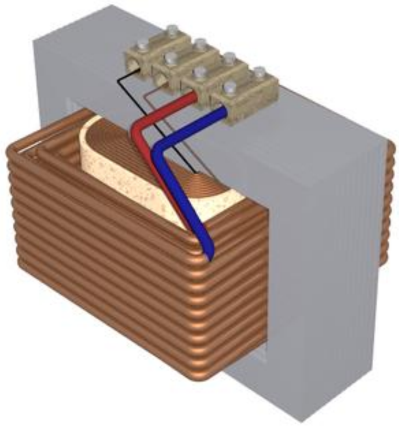
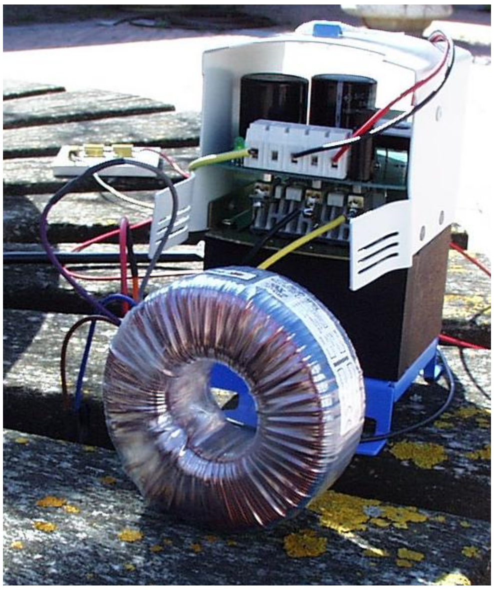


Figure 3. LEFT: the filtered rectifier power supply Legrand-46923. RIGHT: transformer scheme.



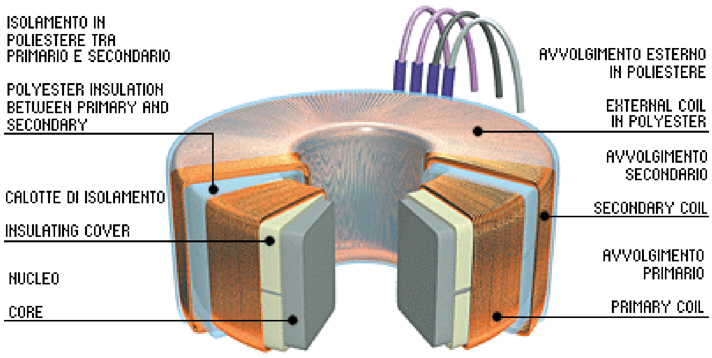


Figure 4. LEFT: the modified Legrand-46923 module (MULTICOMP, Farnel part no. 306-8924, 24V -10A). RIGHT: toroidal transformer scheme.

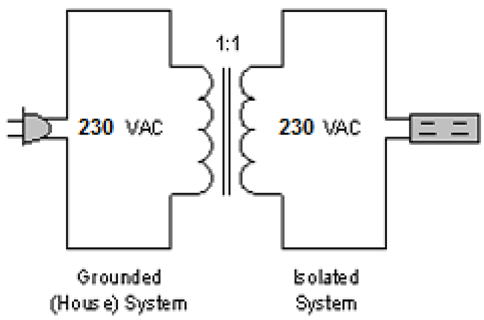


Figure 5. LEFT: isolation transformer Legrand-42446. MIDDLE: transformer configuration. RIGHT: electric scheme.

2. Results

2.1 Notes about seismic noise measurements

For modules L46468 and L46923 ("as is" or modified) the accelerometer shows excess noise at 100Hz, 150Hz, 200Hz and multiples of 50Hz when the module is powered on (Figure 6). No excess noise is measured for the TRACO module. Seismic vibration at twice the AC power frequency and multiples (100Hz and multiples) is indeed expected because of the magneto-striction effect of ferromagnetic cores: magnetic domains of the solenoid core rotate twice as the AC magnetic field changes orientation at each mains voltage cycle. We also observed excess noise at multiples of 50Hz which cannot be explained through the same effect. These might indicate of some sort of Electro-Magnetic pick-up. Also, adding a foam mattress below the device under test with the aim of reducing the transmission of its vibration to the concrete floor did not provide a conclusive result, since we observed a reduction of both the 100Hz and the 50Hz harmonics (Figure 6). We conclude that we need to repeat vibration noise measurement in a more controlled environment.

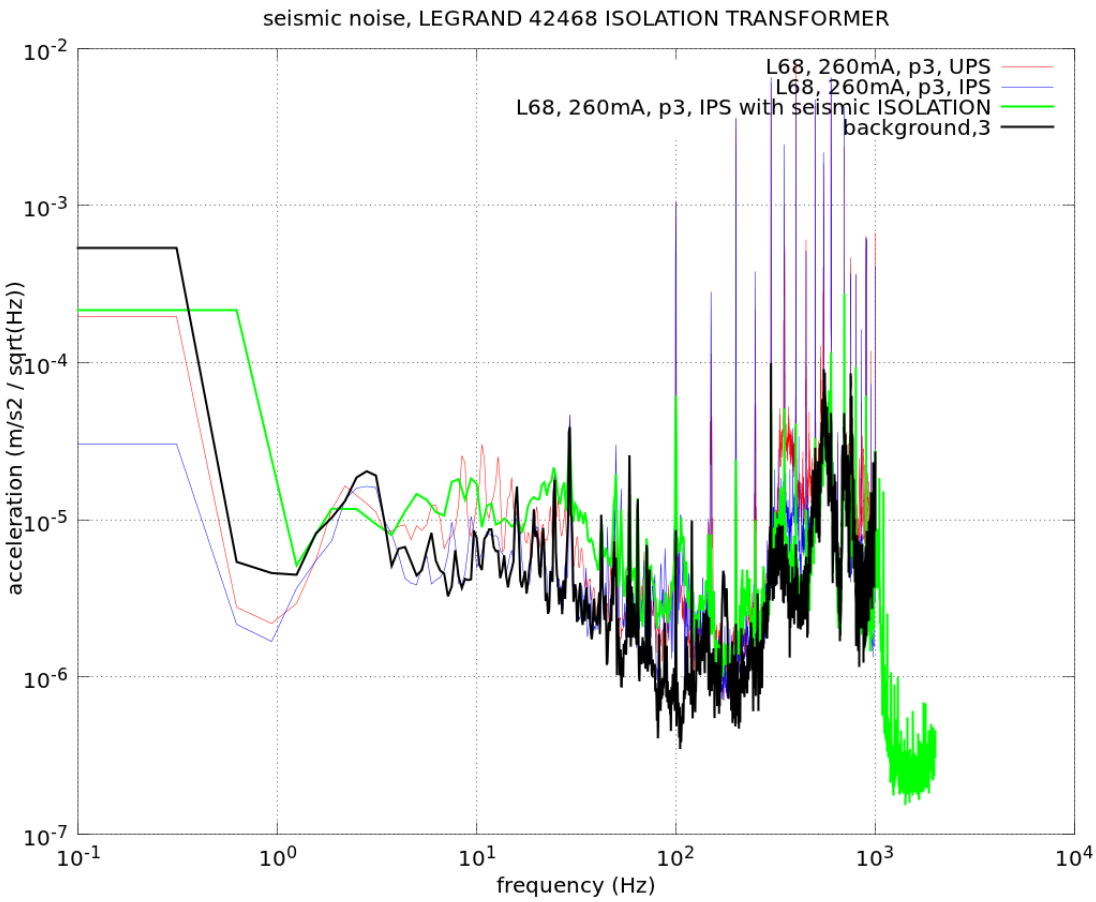


Figure. 6) Vertical acceleration of support slab, when the module L42468 is on the concrete slab and powered (red= with UPS, blue=with IPS), when the module is off (black), and when the module is IPS powered but placed on a foam layer (green).

3.2 Magnetic noise from single modules

3.2.1 Modified L-46923 with toroidal transformer

Replacing the built-in transformer of the L-46923 module with an equivalent toroidal core reduces significantly the stray magnetic field below 500Hz. Figure 7 illustrates the measured vector field magnitude at 0.5m and with similar output current flow (300mA and 350mA as explained in the legend).

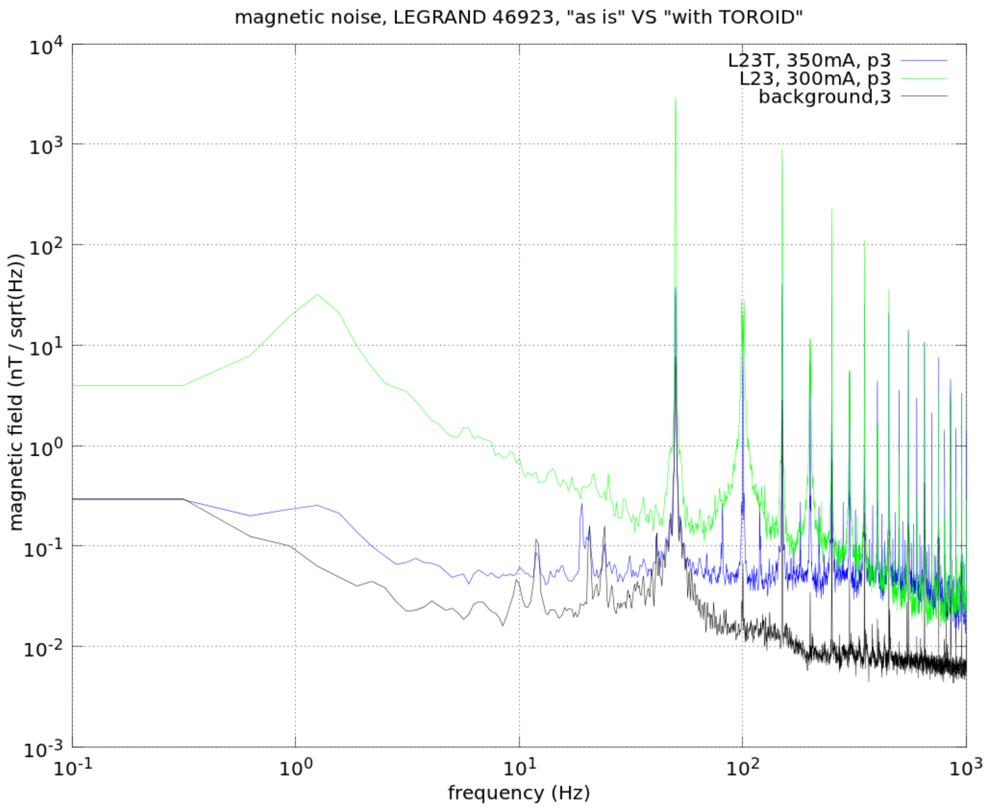


Figure 7) Magnetic field modulus at 0.5m from L-46923 "as is" (green), and when the built-in transformer is replaced with one toroidal shaped (blue). Also shown is the magnetic field measured when the module is off (black).

3.2.2 Magnetic noise isotropy

Figure 8a to 8d show the magnetic field intensity at 0.5m of the four devices. For each unit three measurements were taken changing the module orientation while the probe is fixed. We note a spatial anisotropy of the field intensity which ranges from a factor 2 (Figures 7a and 7b) to a factor 5 (Figure 7c, isolation transformer).

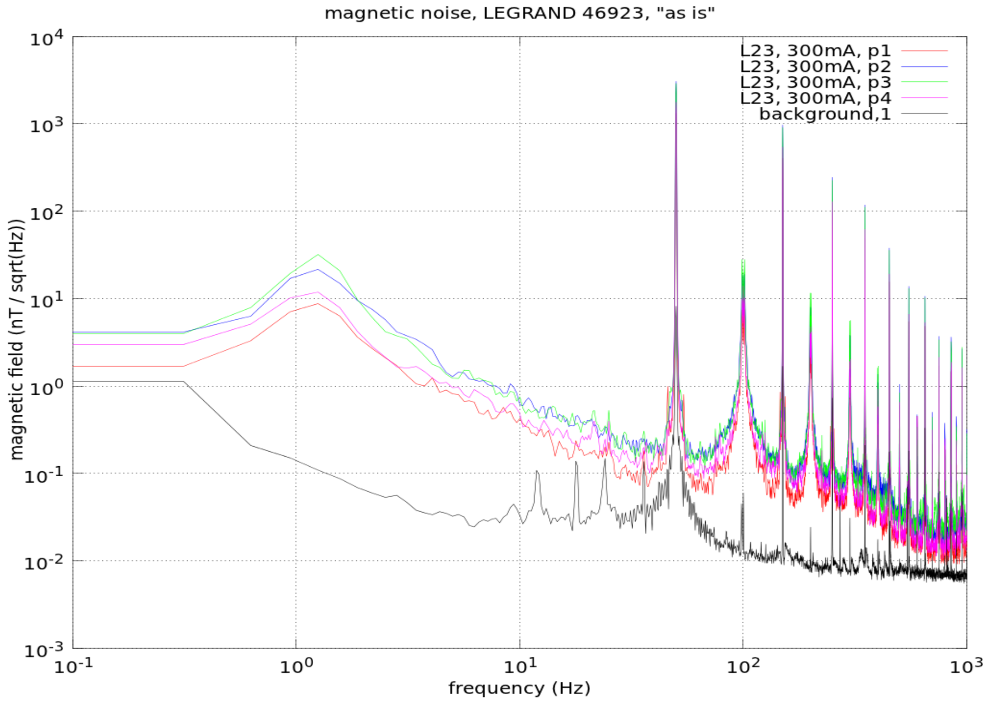


Figure 8.a) Magnetic field modulus at 0.5m from L-46923: colored curves correspond to a different module side facing the probe. Also shown is the magnetic field measured when the module is off (black).

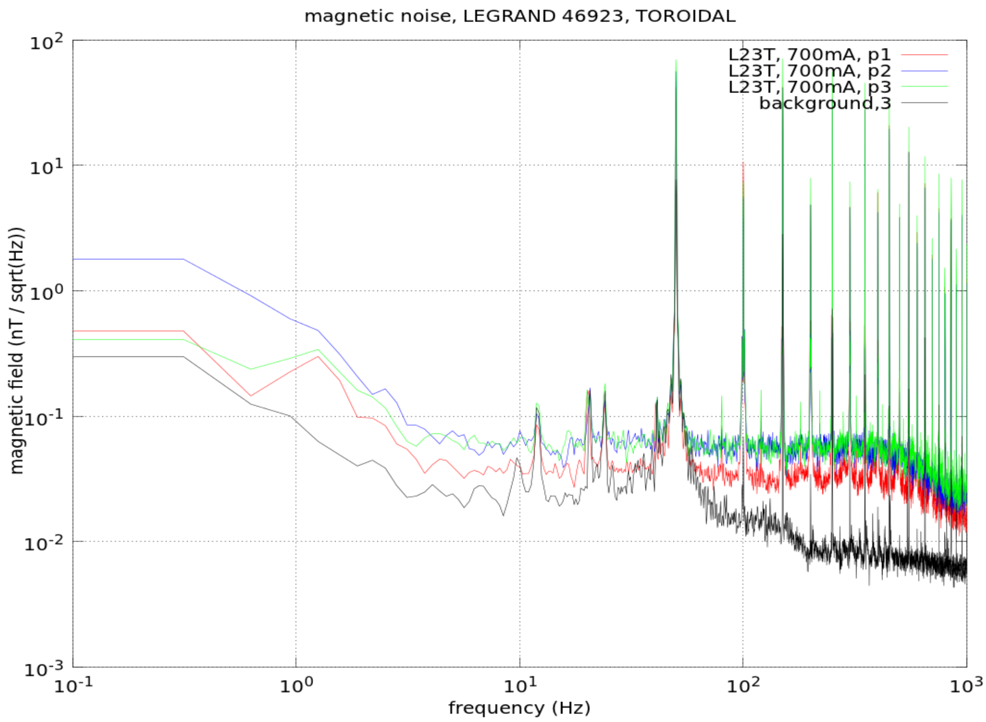


Figure 8.b) Magnetic field modulus at 0.5m from the "modified" L-46923: colored curves correspond to a different module side facing the probe. Also shown is the magnetic field measured when the module is off (black).

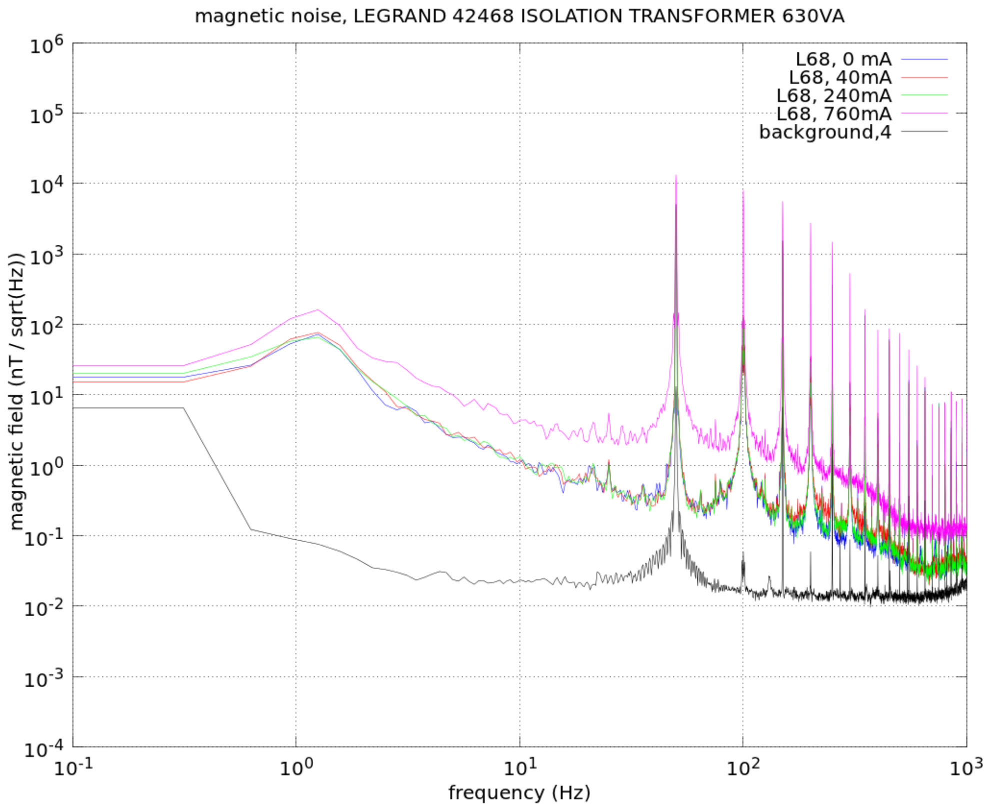


Figure 8.c) Magnetic field modulus at 0.5m from L-42468 (isolation transformer): colored curves correspond to a different module side facing the probe. Also shown is the magnetic field measured when the module is off (black).

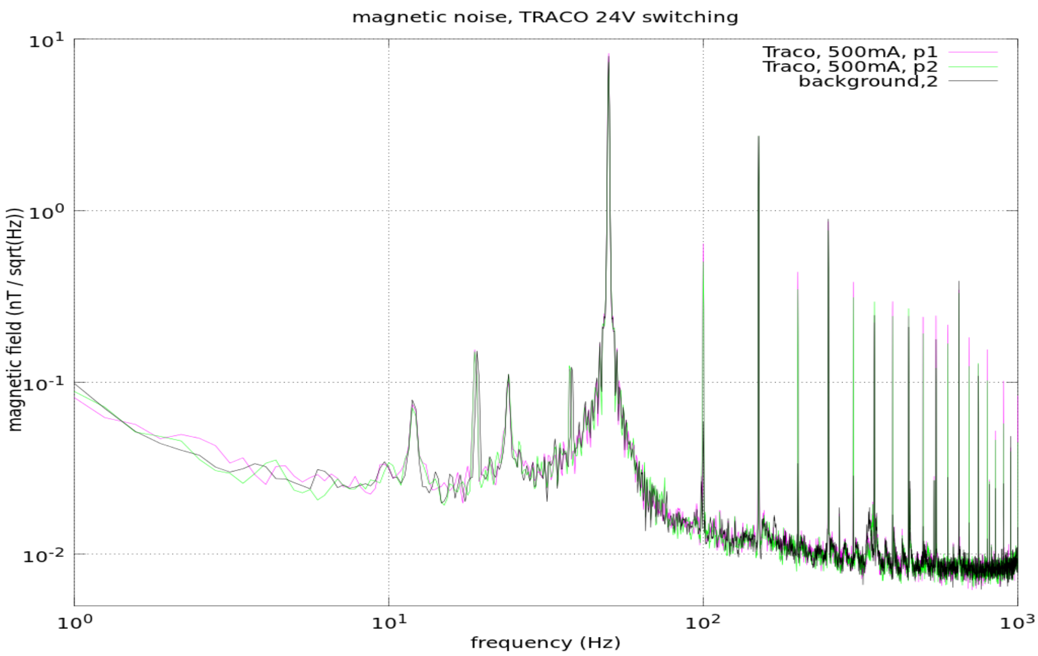


Figure 8.d) Magnetic field modulus at 0.5m from the TRACO module: colored curves correspond to a different module side facing the probe. Also shown is the magnetic field measured when the module is off (black).

3.2.3 Magnetic noise intensity variation with output current

The magnetic field intensity does not change significantly when varying the output current. For output current changing from zero (no load) to about 2A (progressively decreasing resistive load in 3 steps) while remaining within the operating range, the intensity of the stray magnetic field is essentially the same (in Figures 9a to 9e). A peculiar behavior is noted only for the isolation transformers (Figures 9c and 9d) for which the field intensity sensibly increases when the output current exceeded 250mA.

Let us note though that, as reported in Table 1, the operating current of the L46923 and isolation transformers modules is close to zero (<50mA).

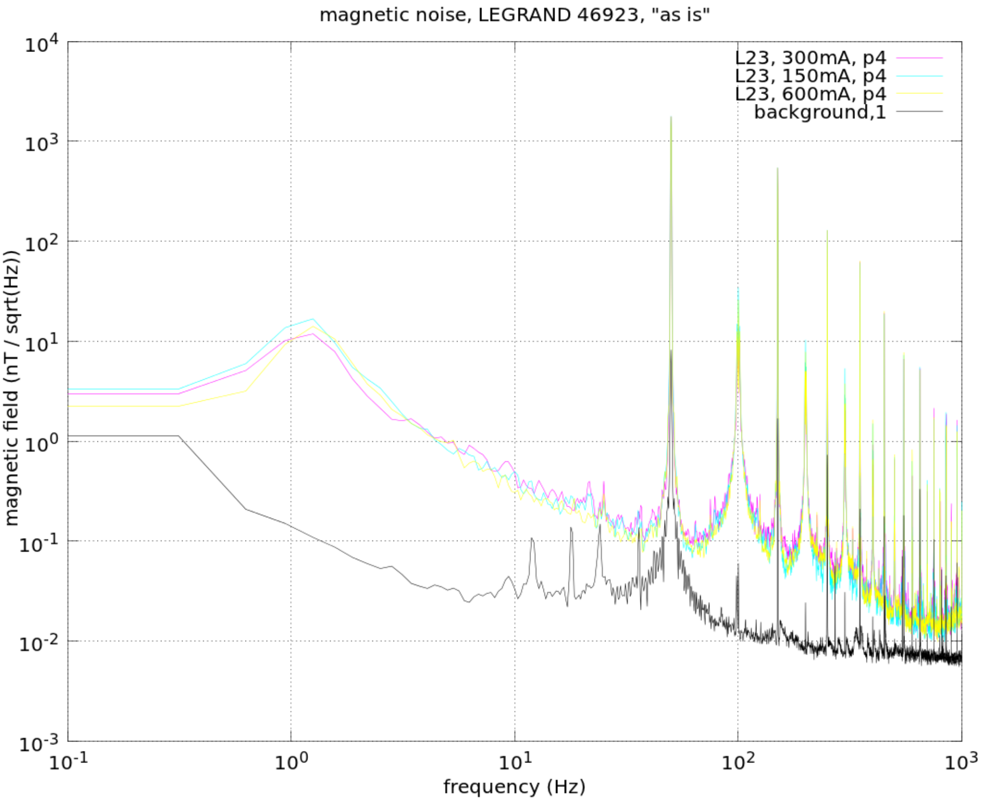


Figure 9.a) Magnetic field modulus at 0.5m from the L-46923 module: colored curves correspond to different output currents (as indicated in legend). Also shown is the magnetic field measured when the module is off (black).

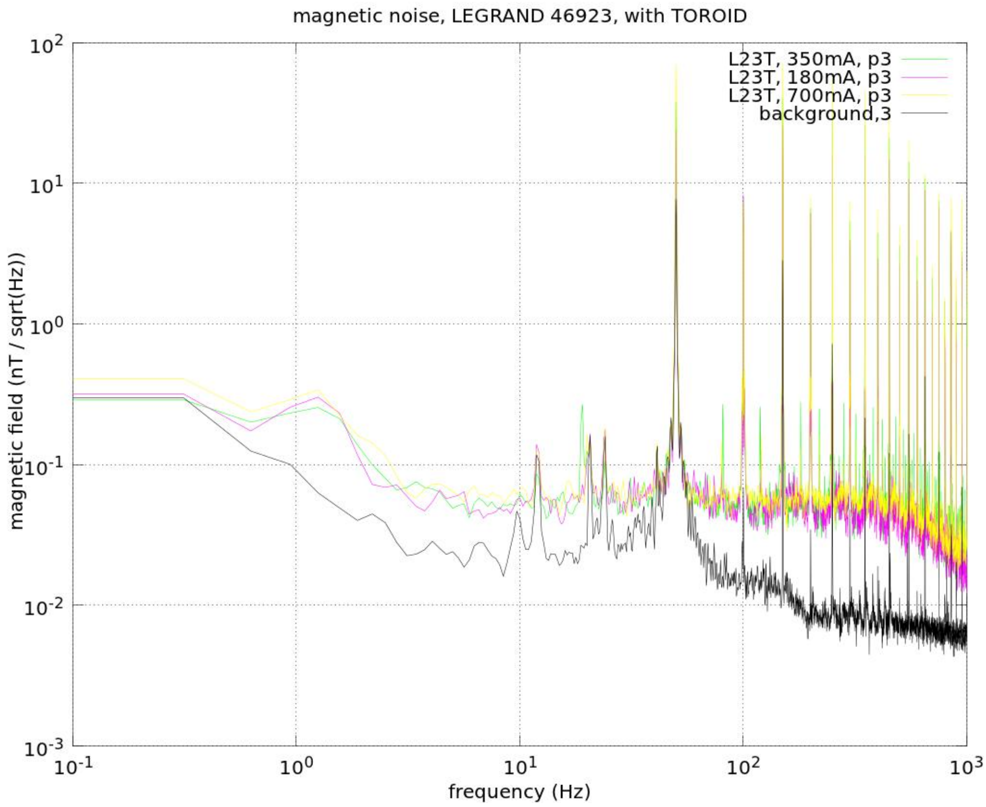


Figure 9.b) Magnetic field at 0.5m from the L-46923 "modified" module: colored curves correspond to different output currents (as indicated in legend). Also shown is the magnetic field measured when the module is off (black).

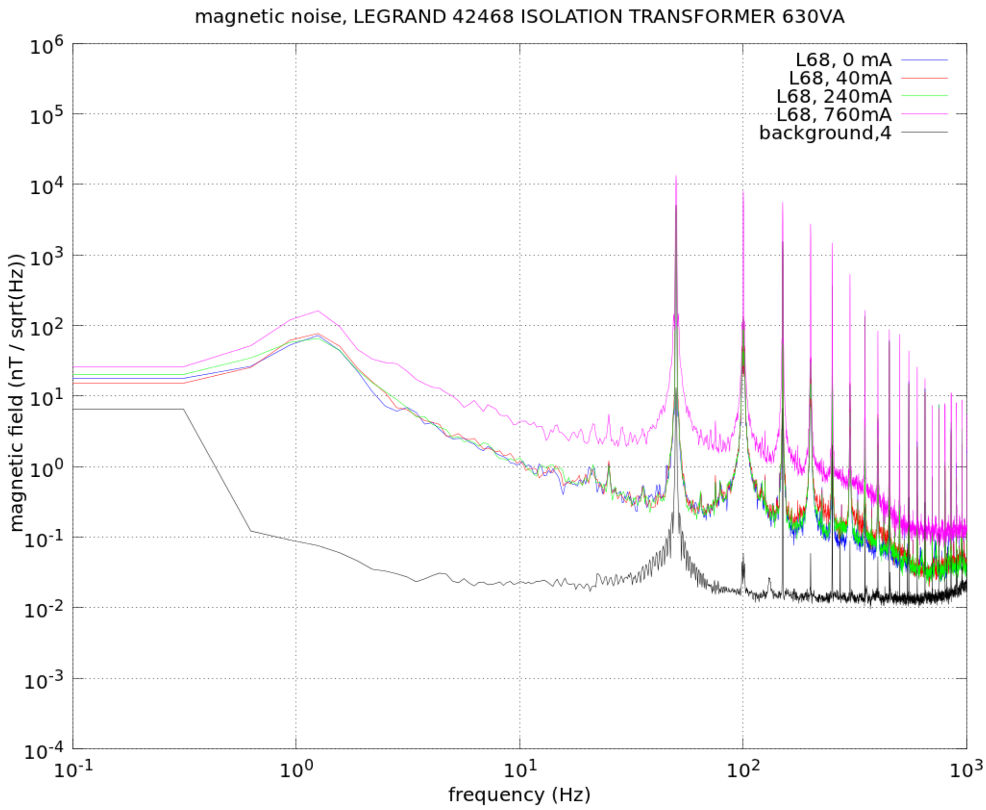


Figure 9.c) Magnetic field at 0.5m from the L-42468 module (isolation transformer): colored curves correspond to different output currents (as indicated in legend). Also shown is the magnetic field measured when the module is off (black).

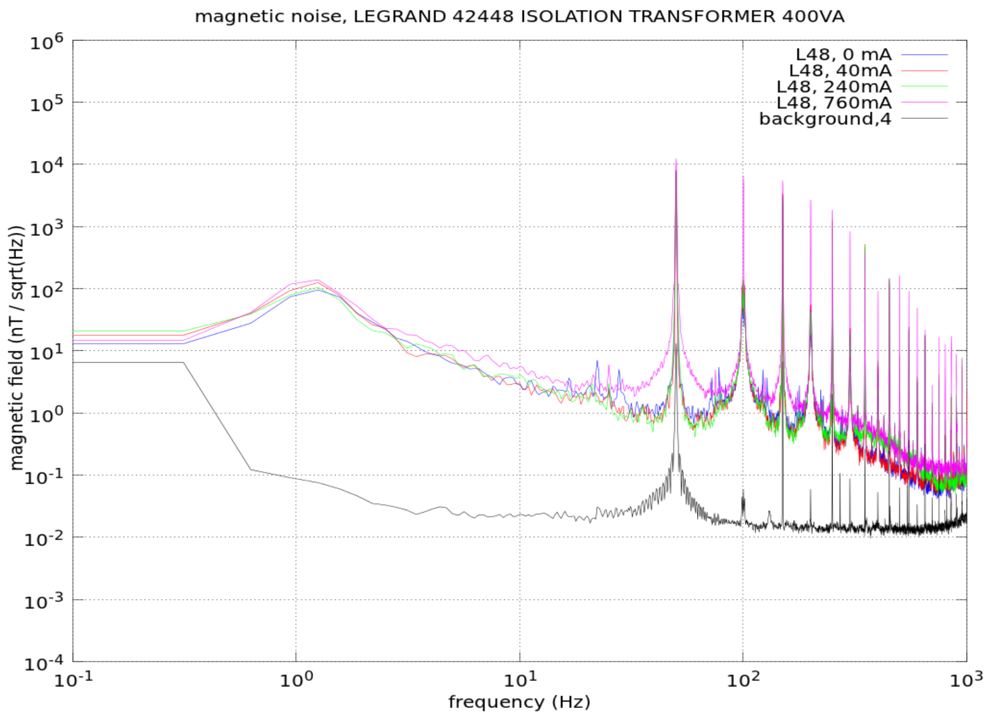


Figure 9.d) Magnetic field at 0.5m from the L-42448 module (isolation transformer for the Pumping Station): colored curves correspond to different output currents (as indicated in legend). Also shown is the magnetic field measured when the module is not powered (black).

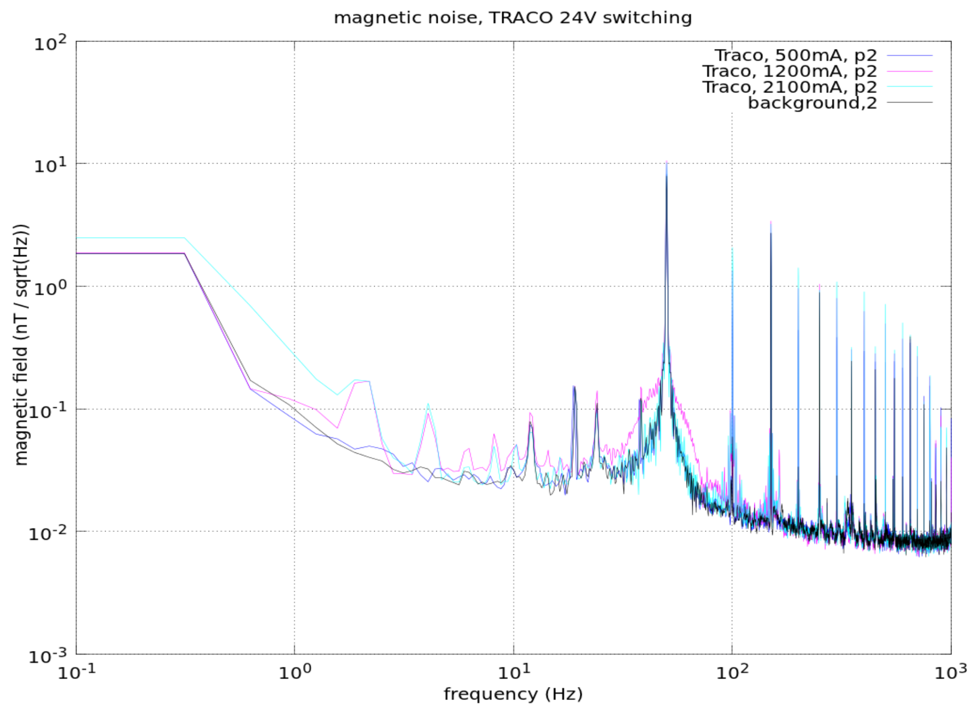


Figure 9.e) Magnetic field at 0.5m from the TRACO module: colored curves correspond to different output currents (as indicated in legend). Also shown is the magnetic field measured when the module is off (black).

3.2.4 Magnetic noise intensity variation with power supply voltage noise

We measured and compared (Figure 10.a) the voltage noise of the mains power line (IPS, also known as ENEL) and of that of the UPS generator (*Riello*, MST 20 T1, total output power 20kVA) that supplies the EGO Office Building. The measurement was taken using an ENEL outlet and a UPS outlet both located in the EGO Electronics Lab. We used one custom made voltage probe consisting of a voltage transformer (230V to 9.3V, 20mA) followed by a 3 to 1 voltage divider: the calibration factor of this probe is thus 74.2 Vin/Vout.

We found that:

- UPS voltage is noisier than IPS, not only because of more intense odd harmonics of 50Hz, but also because of the addition of a white noise extending from at least 1Hz to 1kHz, as illustrated in Figure 10.a.
- The radiated magnetic field intensity is found to increase more or less proportionally to the voltage noise. Figure 10.b compares L-42468 stray magnetic field intensity when the module is powered on IPS and UPS.

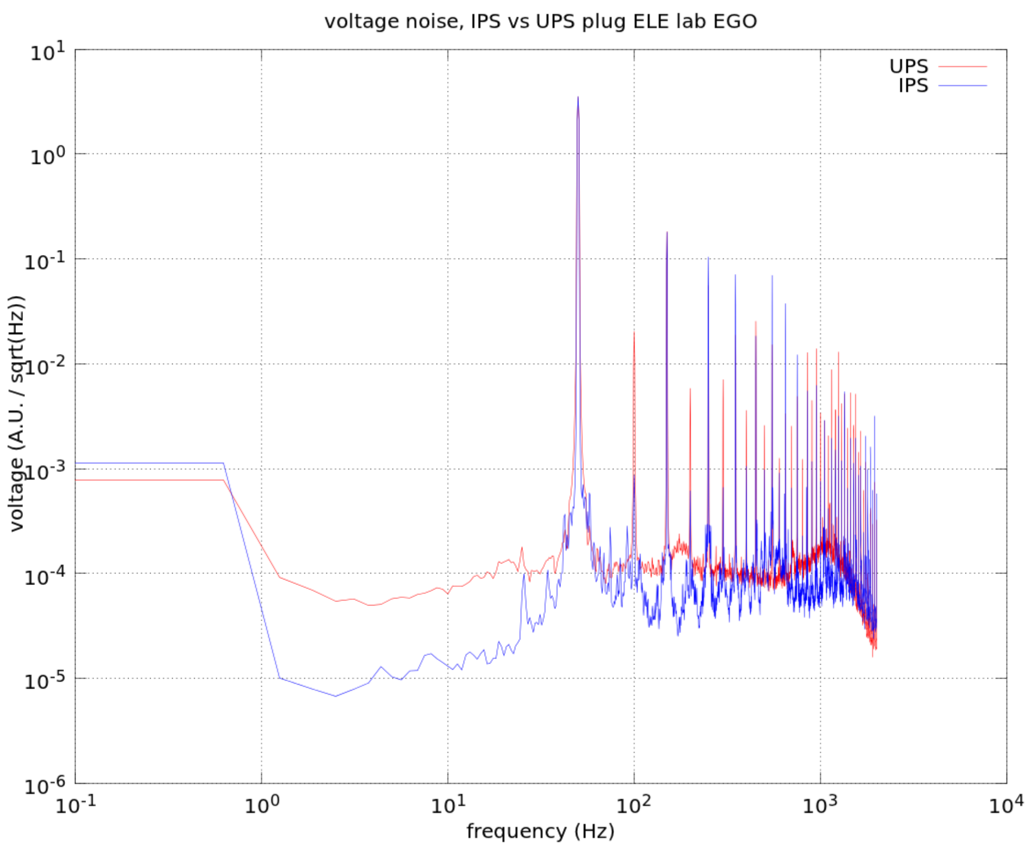


Figure 10.a) RED: Voltage noise of the UPS line used for all measurements; BLUE voltage noise of the IPS (ENEL) line. To get to physical units (Volts) vertical scale values must be multiplied by a factor 74.2 (see text).

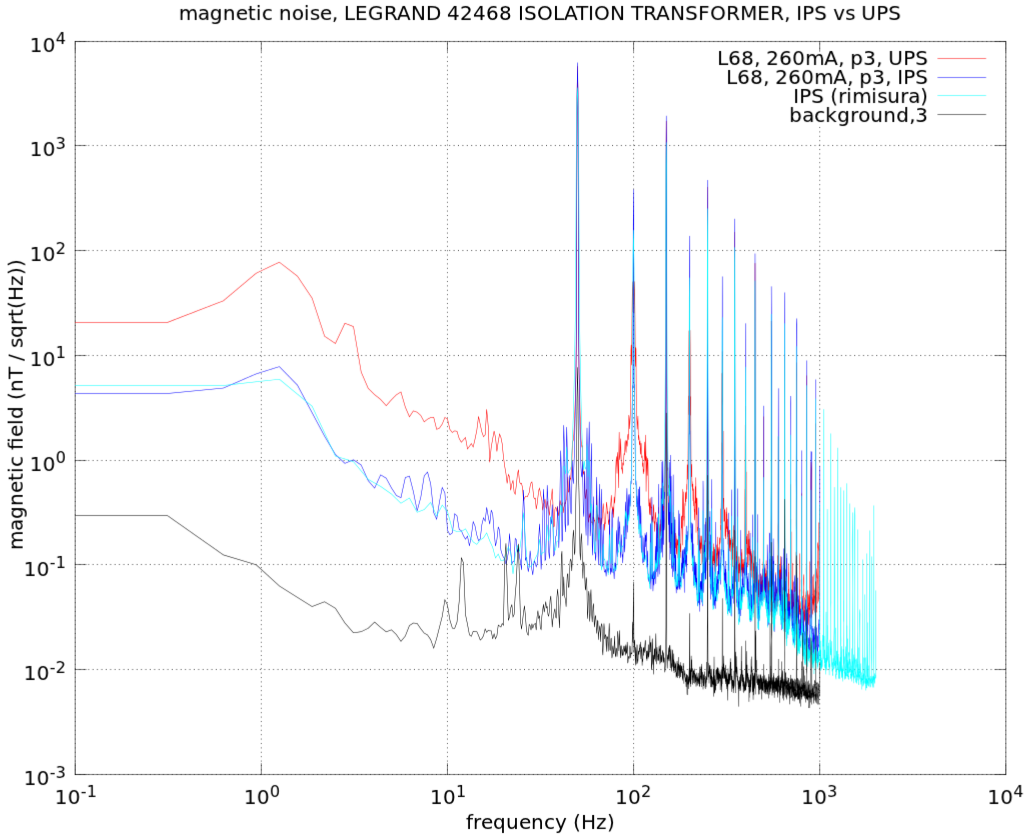


Figure 10.b) Magnetic field at 0.5m from the L-42468 isolation transformer module: the RED curve corresponds to the module powered through UPS in the EGO Electronic Lab (the same plug used for all above measurements); the BLUE and CYAN curves correspond to the module powered with IPS. Also shown is the magnetic field measured when the module is off (black).

3.3 Magnetic noise from NI tower rack

We measured magnetic field intensity in some positions around the NI tower vacuum rack. The rack sits on the platform, which is made of steel beams and aluminum tiles (Al is paramagnetic, while steel is ferromagnetic). This rack was powered on, while all other racks (SR and DET vacuum racks and all suspension racks) and power supplies in the rack's vicinity were off. The rack was then the major source of magnetic noise within the probe range, for each probe location. The NI rack is powered with a Merlin-Gerin's UPS 200kVA machine. We put the FL3-100 magnetic probe at distances of 0.5m, 1m, 1.5m, 3m, 4m and 5m measured from the geometric center of L-46923 and L-42468 rack modules pair (Figure 1a). The probe was sitting onto a plastic support holding it at about 0.5m above the platform floor. In each location the probe was pointing towards the rack.

Figure 11.a compares the B modulus measured at 50cm from the rack and the quadratic sum of the B modulus measured at 50cm from the single L-46923 and L-42468 modules in the Lab. The latter is about a factor 8 less noisy, as shown in Figure 11.b (red curve). This "missing" factor could be explained by the fact that the voltage noise of the UPS outlets used (blue in Figure 11.b) is about a factor 10 larger for the NI rack (200kVA Merlin Gerin's UPS) than it was for the Lab measurements (Riello's 20kVA UPS). Figure 11.c compares the voltage noise of the Lab. UPS, the central hall UPS, and the IPS.

- Our conclusion is that, the stray magnetic field measured around the rack roughly corresponds to that measured in the Lab on single modules, amplified by the power line voltage noise.

Figure 11.d shows the measured magnetic field modulus at increasing distances from the NI rack, from 0.5m to 5m. Up to 4m from the rack we note a wide-band decrease of the magnetic field. Since the rack is the only relevant magnetic noise source within this range, Figure 11.d indeed maps the spatial decrease of the noise generated by the rack. The intensity roughly decreases as the square of the distance from the rack: noise decrease is about a factor 100 as moving from 0.5m to 4m away from the rack (blue to green in Figure 11.d). After that, moving further away from the rack does not cause any further decrease of the magnetic field intensity. It is likely that at about 4m distance from the rack the background magnetic field starts dominating over other (distributed) sources (power cables?).

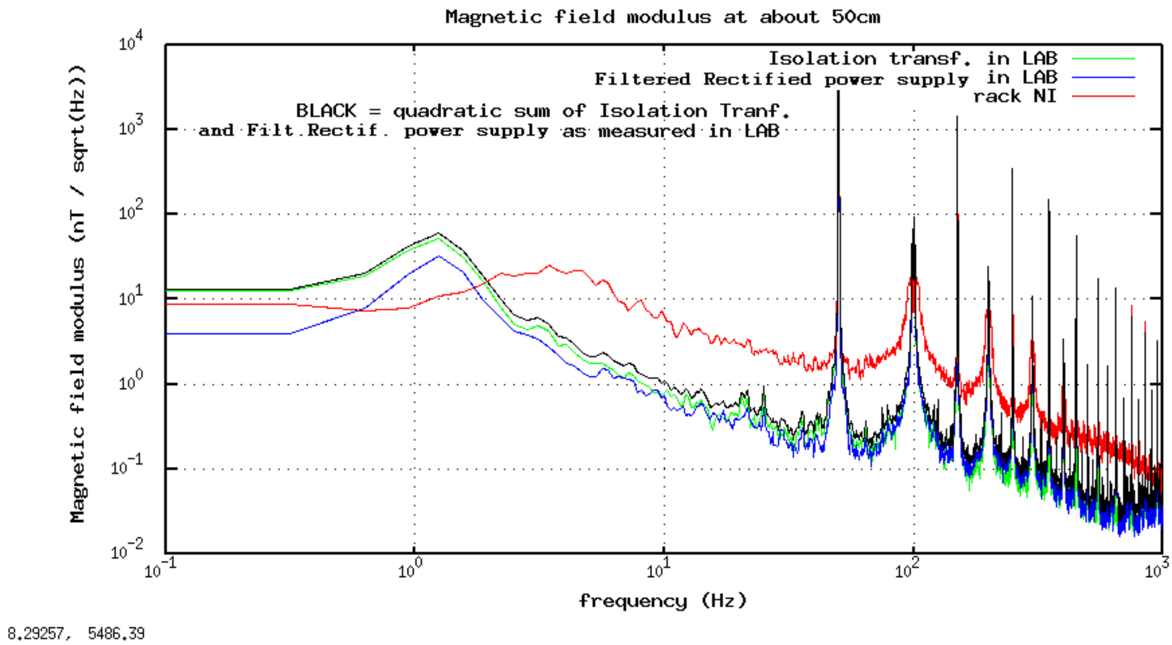


Figure 11.a) Magnetic field modulus at 0.5m from sources: (red) measured at NI vacuum rack, powered at Central Building UPS outlet; (black) quadratic sum of magnetic field of L-46923 (blue) and L-42468 (green) modulus as measured in the Lab. and powered through a Riello UPS outlet.

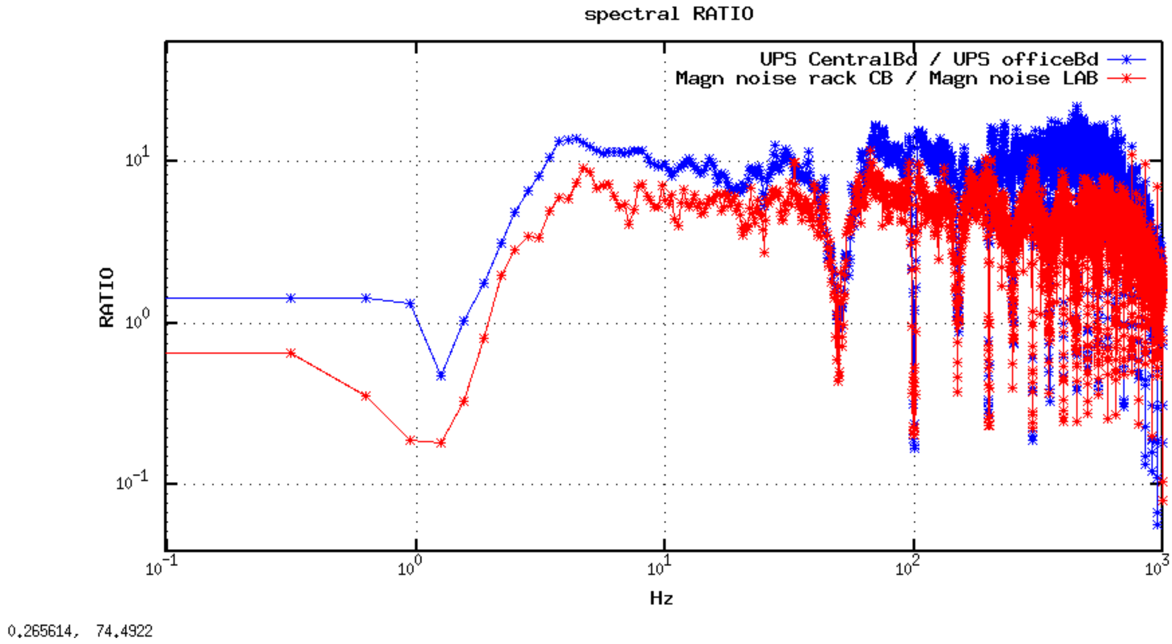


Figure 11.b) (blue) Ratio of the voltage noise of UPS used to power NI vacuum rack and UPS used to power modules in Lab tests; (red) Ratio of magnetic noise modulus measured at the NI vacuum rack and "expected" at the NI vacuum rack from extrapolating measurements of Lab tests.

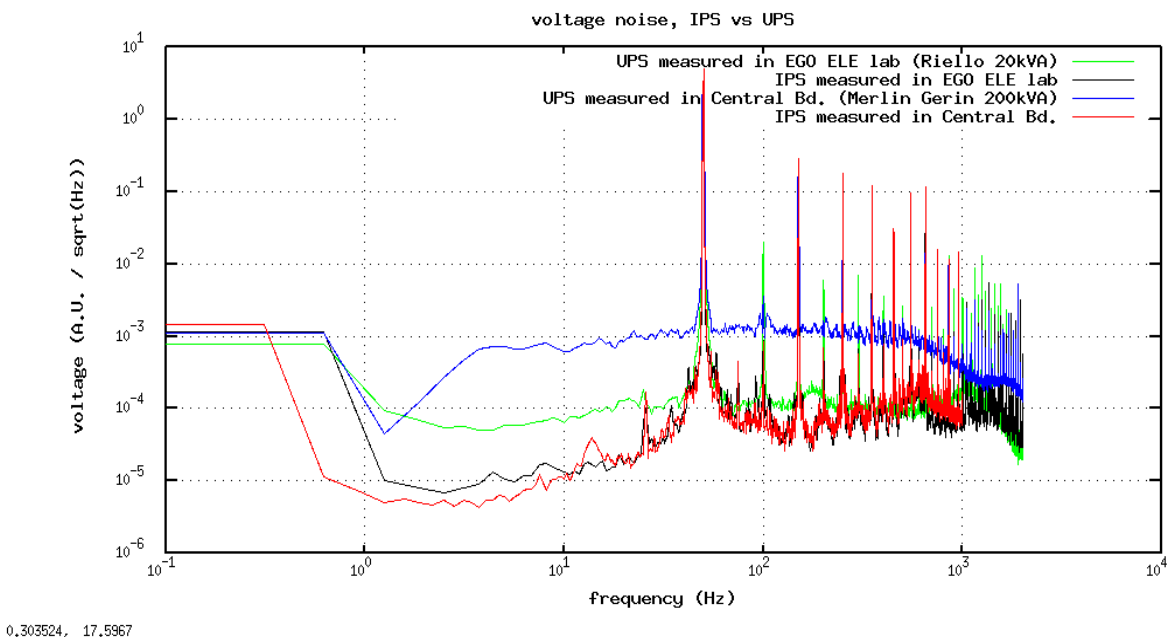


Figure 11.c) Voltage noise: (blue) Merlin Gerin's 200kVA UPS, at NI vacuum rack; (green) Riello's 20kVA UPS in tests Lab; (red and black) IPS.

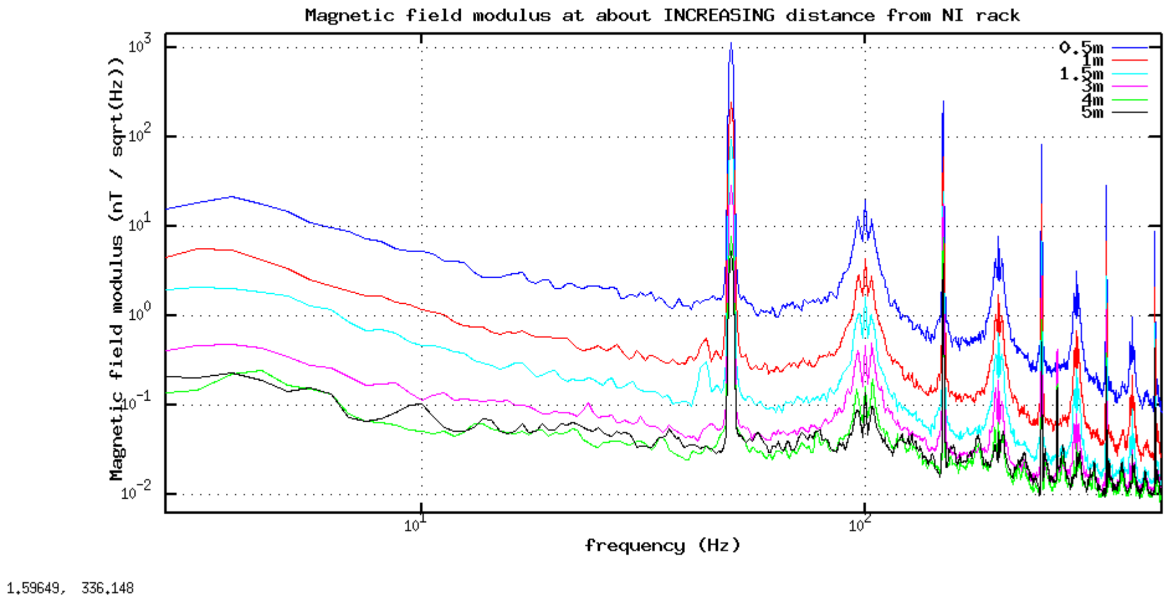


Figure 11.d) Amplitude spectrum of magnetic field modulus at increasing distances from NI vacuum rack: 0.5m (blue), 1m (red), 1.5m (cyan), 3m (magenta), 4m (green) and 5m (black).

4 Conclusions

Through our measurements "on the bench" we identified two components of the Vacuum power supply modules that produce relevant stray magnetic fields: (1) the filtered rectifier power supply (Legrand mod.46923) and (2) the isolation transformer (Legrand mod.42468). The radiated magnetic noise of the two is similar and consists of a sort of broadband pink noise starting from very low frequency (<1Hz) with the addition of characteristic double-peak structures around 100Hz and multiples (see Figure 12).

We verified that the magnetic stray fields of the filtered rectified power supply can be significantly reduced by replacing its input transformer with one having a toroidal core. This modification allows a substantial reduction of the noise below 500Hz: the broadband noise decreased by more than a factor 10 below 10Hz, and by about a factor 5 between 10Hz and 100Hz. Structures around 100Hz and its multiples disappeared (in Figure 12).

We also verified that magnetic fields radiated by the power supply increase proportionally to its voltage noise.

Stray magnetic noise measured on single components on test bench appears consistent with the noise emitted from vacuum racks in the field, once accounting for amplification due to additional UPS power noise.

Stray magnetic field intensity roughly decays with the second power of distance from the rack. At about 5m distance the rack stray magnetic field appears to have similar intensity as the magnetic noise background generated by other sources in the experimental hall.

We then derive some guidelines to help mitigating stray magnetic noise in AdV experimental halls:

- Use only linear power supply having toroidal transformer core;

- When purchasing UPS generators it is fundamental to evaluate their output voltage noise;
- It would be preferable to power electronic equipment located close to sensitive apparatus (like suspended mirrors and benches) using small size and low noise UPS machines. The Riello's 20kVA seems a good solution. The same UPS machines are adopted also at NE and WE terminal building, while MC building adopts one Riello's 10kVA. Figure 13 compares the UPS voltage noise at Virgo Central Building, Terminal buildings, and MC building. The noise level of Terminal buildings UPS line is similar to that of the Office building (Figure 11.c), while MC line is even less noisy.

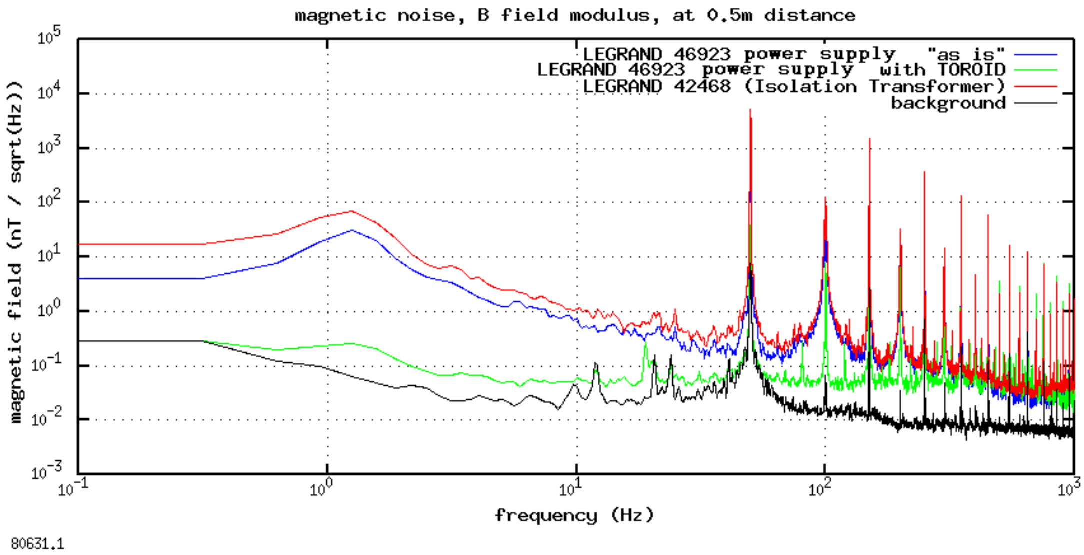


Figure 12) Magnetic field modulus at 0.5m distance from: (red) Legrand-42468 isolation transformer; (blue) Legrand-46923 power supply "as is", Legrand-46923 power supply with toroidal transformer (green). Black line corresponds to the residual noise (modules OFF).

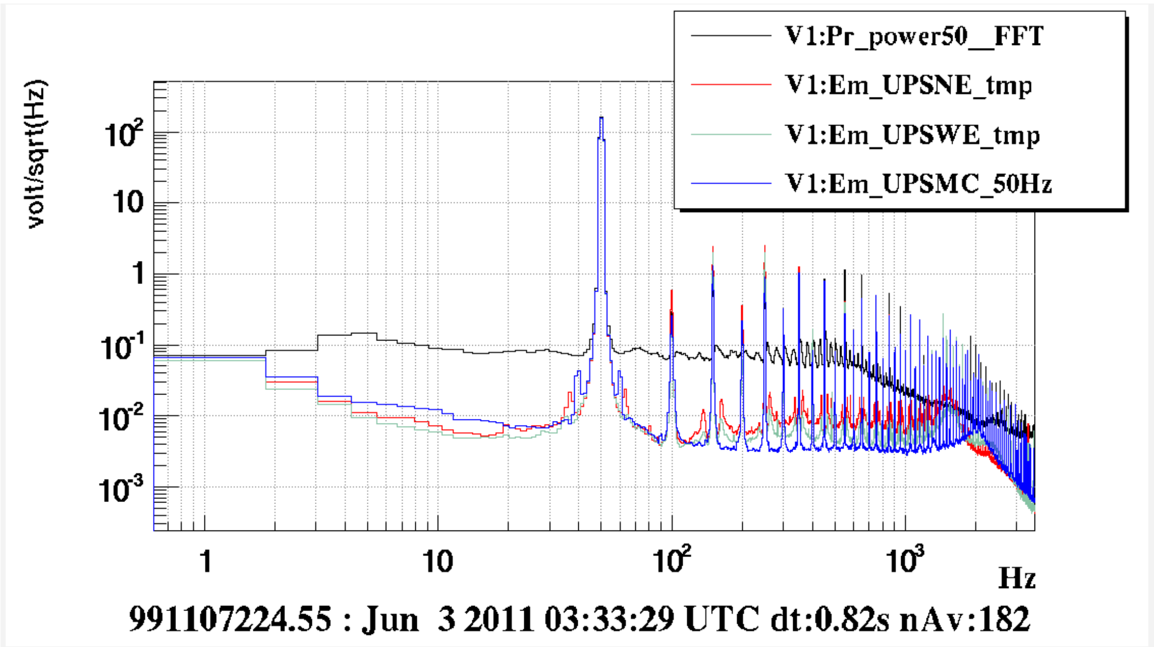


Figure 13) Voltage spectral noise of UPS lines in Virgo experimental Buildings. Black: Central (served by MGE UPS 200kVA), Red: North-End (served by Riello UPS MST 20 T1 20kVA), Green: West-End (served by Riello UPS MST 20 T1 20kVA), Blue: Mode-Cleaner (served by Riello UPS MLT 10 A5 10kVA).

References:

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