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VIRGO Collaboration

DAC Noise Effect on VIRGO Sensitivity

Commissioning Report MSC-401

Document Number: VIR-006A-09

Issue: 1.0

Date: 04/03/2009

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Change Record

Issue	*Date*	*Affected Paragraphs*	*Reason/Remarks*	*Author*
1.0	04/03/2009	All	First release	A. Gennai

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1. INTRODUCTION

1.1 *Purpose*

This document summarizes results from measurements taken during a devoted commissioning shift of March 3rd, 2009. Shift was aimed to a direct measurement of noise produced by DAC (Digital to Analog Converter). For that purpose we selected Marionette horizontal actuators (coils on Filter#7, magnets on Marionette).

1.2 *Scope*

This document covers three main aspects. The first introductory part shows laboratory measurements used to obtain a model for DAC noise. The second part presents measurements made using Virgo and finally the third part of this document presents actuators noise budget based on new measurements.

1.3 *Acronyms*

This document contains several abbreviations and acronyms to refer concisely to an item after it has been introduced. The following list is aimed to help the reader in recalling the extended meaning of each short expression.

DAC	Digital to Analog Converter
DNL	Differential Non Linearity
DSP	Digital Signal Processor
LSB	Least Significant Bit
THD	Total Harmonic Distortion
VME	Versa Module Eurocard
VSB	VME Sub-System Bus

1.4 *References*

This report refers to the following documents containing background or detailed information that can be useful for the reader.

[RD1] AD1862 Datasheet

http://www.analog.com/en/obsolete/ad1862/products/product.html

[RD2] Virgo Noise Budget

http://olserver31.virgo.infn.it/Noise/html/index.php?callContent=28

2. DAC NOISE: LABORATORY MEASUREMENTS

2.1 *DAC Converter*

All measurements reported in this document were performed using the VME/VSB board named DAC820d. The board, 8 channels, 20-bit, is capable of operating up to 500 kHz conversion rate. Differential output dynamical range is 20 V peak to peak. In Virgo DAC820d board is used in the control of suspensions and is normally operated at 10 kHz.

Board, manufactured in 1997, is based on converter AD1862 [RD1] by Analog Devices, now obsolete.

2.2 *DAC Noise*

DAC noise was measured several times in laboratory. Measurements reported in this section were performed one year ago (January 2008) and presented to the Virgo Collaboration on January 30th 2008. When the DAC input (digital) is set to zero, output noise spectra is shown in the following picture where the DAC noise is shown superposed to a noise model.

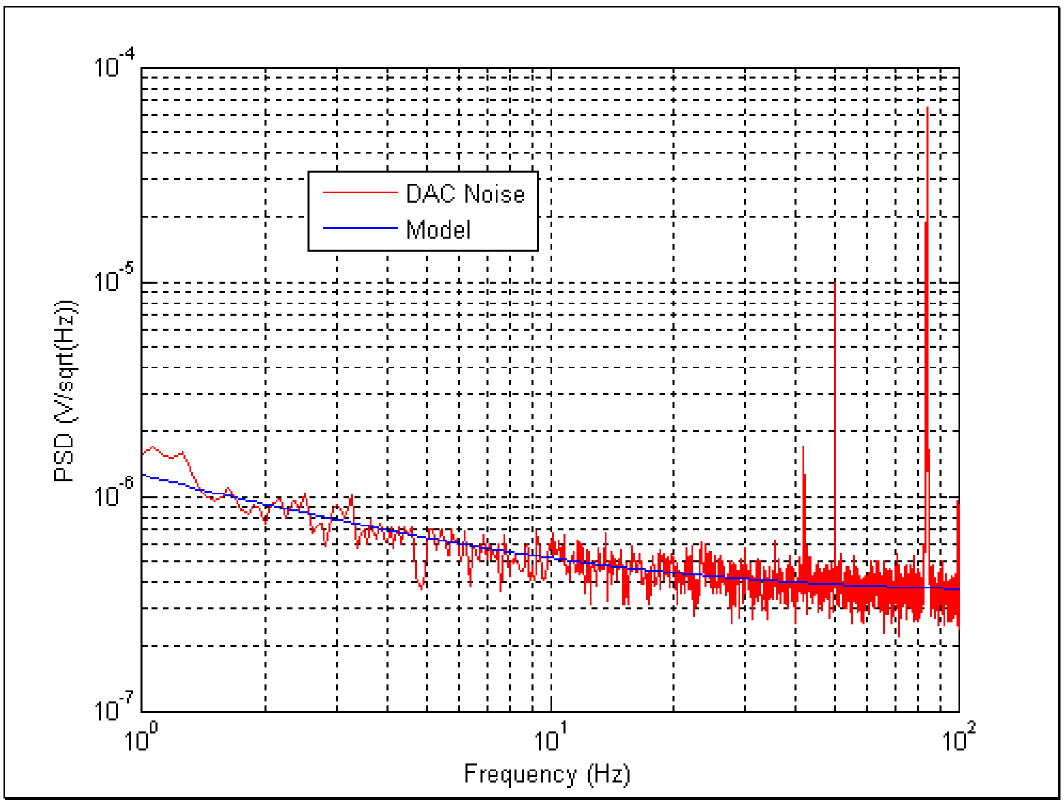


Figure 1 DAC noise (Vout = 0 Vdc)

When DAC input is set to zero, its noise fits with the following model:

$$\tilde{N}_L \cong \frac{1.5 \cdot 10^{-12}}{f} + 1.2 \cdot 10^{-13} \quad \frac{V^2}{Hz}$$

When we drive the DAC with a lowpass signal the DAC noise at higher frequency than the input signal grows up due to DAC DNL (Differential Non Linearity) error[1]. The following picture shows the DNL measured for a much reduced set of DAC codes (500 over a total of 2^20 codes). Reader shall notice that in average DNL error is very small (a fraction of 1 LSB) but for some code error grows up to 5 LSBs.

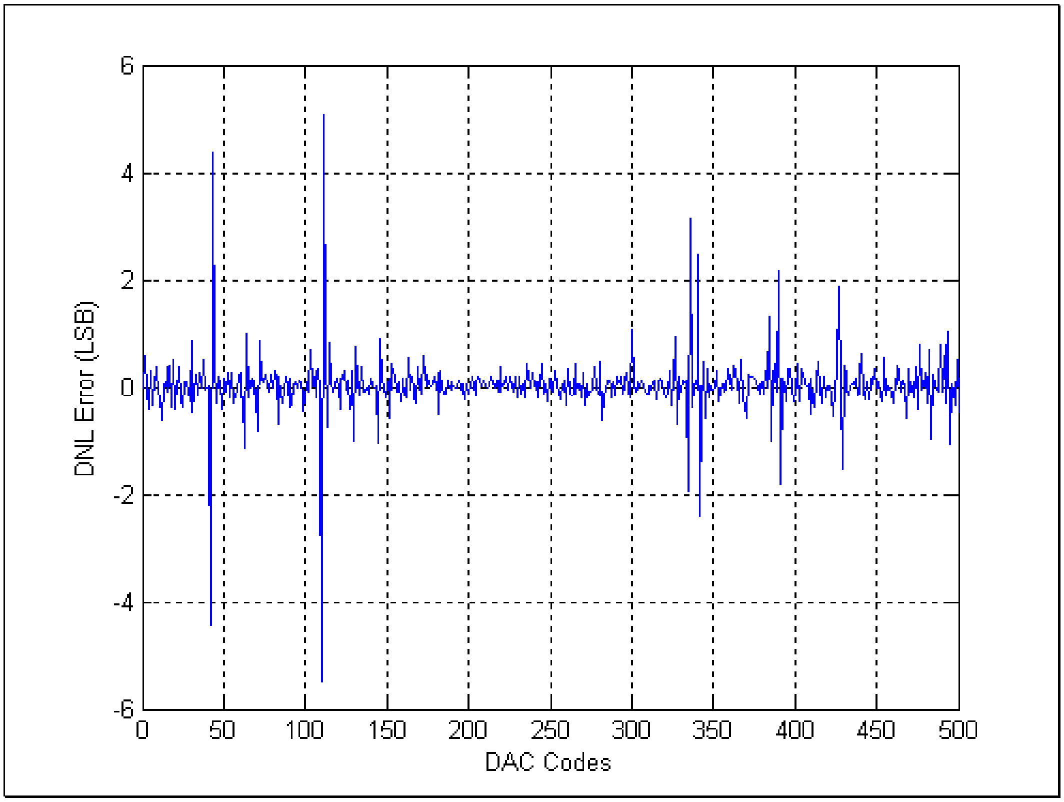


Figure 2 DNL Error for a few DAC codes

Due to the DNL error, DAC produces an up conversion of low frequency noise. The effect is evident both measuring the harmonic distortion (THD) when driving the DAC with a sine wave and driving the DAC with a lowpass signal. The following picture shows what happens for increasing rms values of the input signal (only partially visible and only for highest rms values). Output signal was low pass filtered before entering the spectrum analyzer to minimize analyzer noise (and up conversion).

[1] DNL error is the difference between ideal and measured output for successive DAC codes

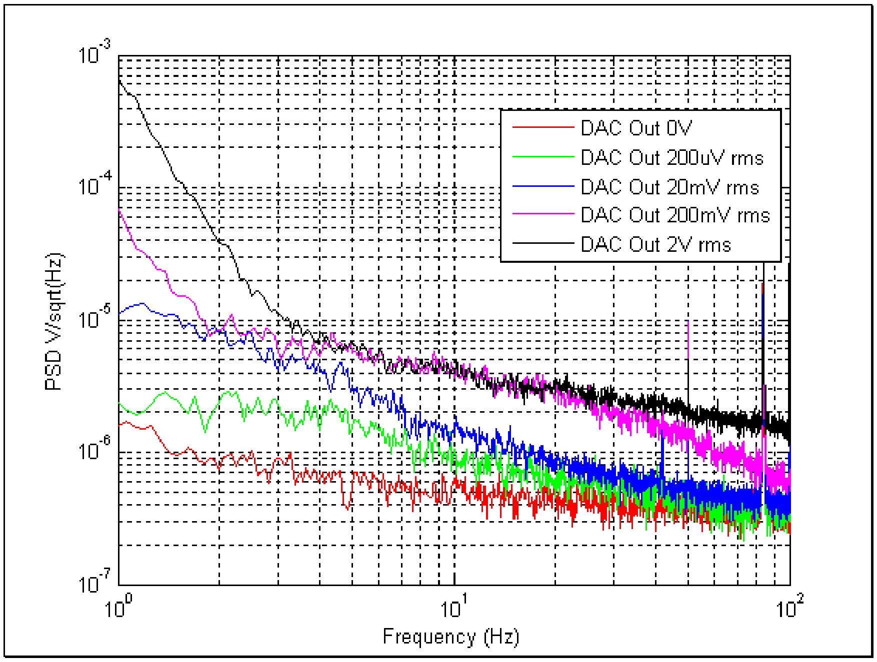


Figure 3 Up conversion for different low frequency signal levels

From Figure 3 we can see how noise increases together with the rms value of input signal. At 10 Hz for example, noise spectra varies from about 0.5 uV/rtHz up to 4 uV/rtHz and we can see that as soon as input signal reaches 200 mVrms, noise spectra "saturates" at 4 uV/rtHz.

DAC noise is therefore a function of input signal and we can assume as upper limit the model shown in the following picture: at 1 Hz noise can be 10 times larger than "zero output" noise.

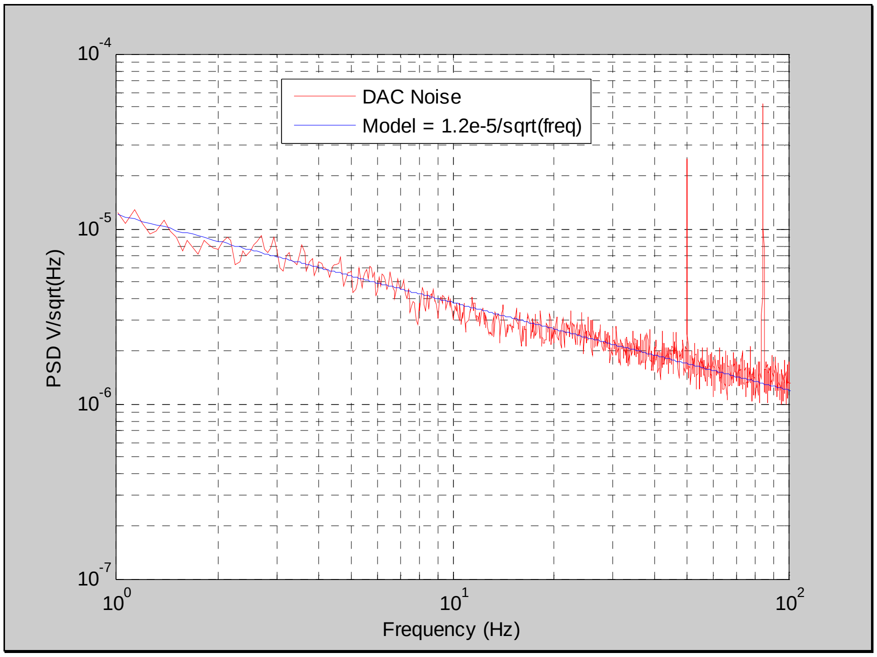


Figure 4. Modelling DAC Noise: DNL Effect

2.3 *Dithering*

As soon as we get to the conclusion that the DAC was producing up conversion due to DNL error we made some test to check the hypothesis. If up conversion comes from DNL adding a small high frequency signal we force an average on several DAC codes reducing the non linearity (see Figure 2). This technique is known as "dithering" and is widely used in digital signal processing to reduce quantization effects. The following signal (about 20 mV rms) was added to the lowpass signal.

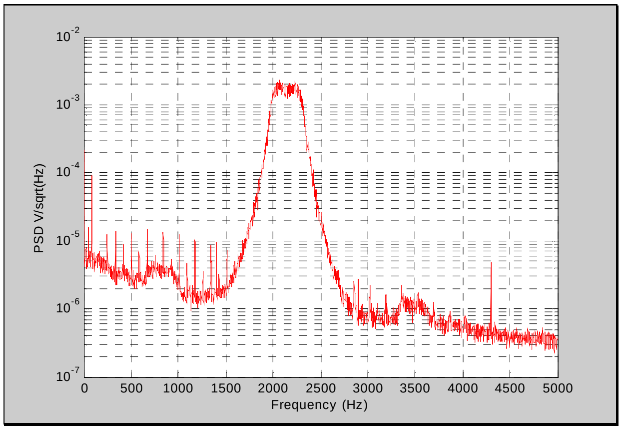


Figure 5 Dither signal

Effect of dithering is shown in the following pictures. DAC output noise at 10 Hz is reduced by a factor 4 and

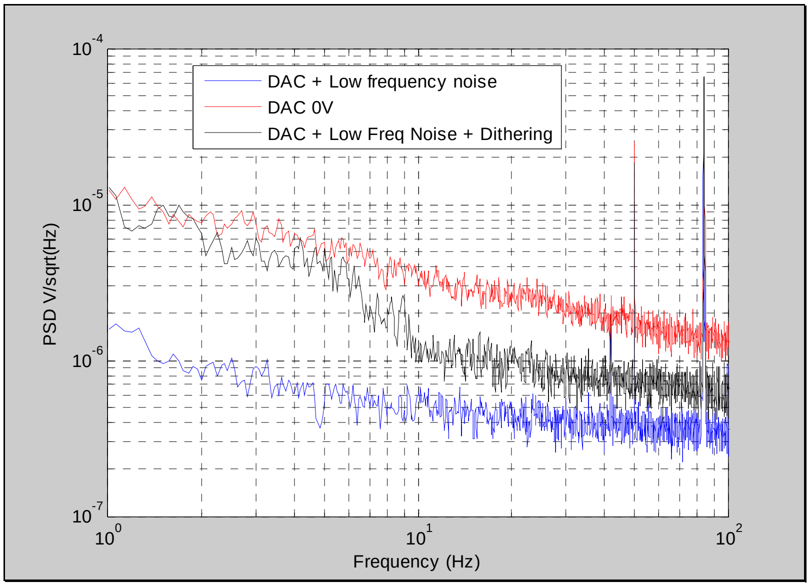


Figure 6 Dithering Effect: up conversion is significantly reduced

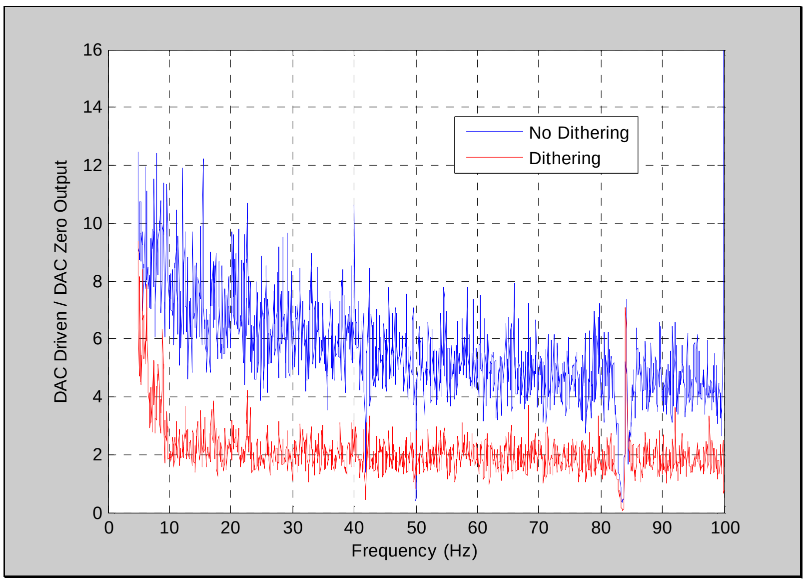


Figure 7 Noise increase in respect with a DAC with zero input

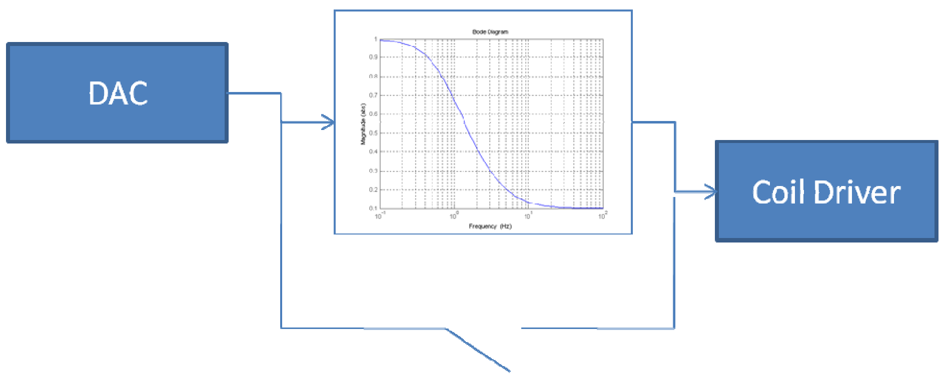
Laboratory test conclusion was that DAC noise cannot be larger than twice the nominal DAC noise if DAC input signal has enough high frequency components to produce a dithering effect (otherwise such signal should be added).

3. VIRGO MEASUREMENTS

This section reports about DAC noise measurements that took place during a devoted commissioning shift on March 3rd, 2009.

3.1 *Actuators Noise: Marionette Arms*

Noise of DAC channels driving Marionettes on long arms (North Input, North End, West Input and West End suspensions) was indicated to be one of the highest noise sources in Virgo Noise Budget [RD2]. DAC outputs are lowpass filtered in order to reduce by a factor 10 the noise contribution above 10 Hz. The filter is implemented using a capacitor that can be easily excluded using a switch. In standard operation filter is on.



When lowpass filter is excluded (and also its highpass digital counterpart implemented in DSP), DAC noise contribution is increased by a factor 10.

Removing lowpass filters from marionette actuators on long arms we can see the effect of DAC noise on Virgo sensitivity (Figure 8). Below 40 Hz sensitivity is affected by DAC noise and at 10 Hz sensitivity grows from about 2e-20 up to 5e-20 1/rtHz. Inserting back lowpass filters at input suspensions (NI and WI) did not produce any change in the sensitivity apparently due to the fact that DAC output is much smaller at input towers and therefore up conversion is negligible. From this plot we can compute DAC noise levels assuming the following values for transfer function between DAC output and mirror displacement:

DC Displacement: 3.4 um/V (using both horizontal coils, each coil contributes with one half of this value).

First Marionette Resonance: 450 mHz

Second Marionette Resonance: 980 mHz

Result is shown in Figure 9 where measured DAC noise level is compared with the model described in Section 2.2 (black line). DAC noise dominates sensitivity between 5 and 40 Hz and is smaller than what observed in laboratory.

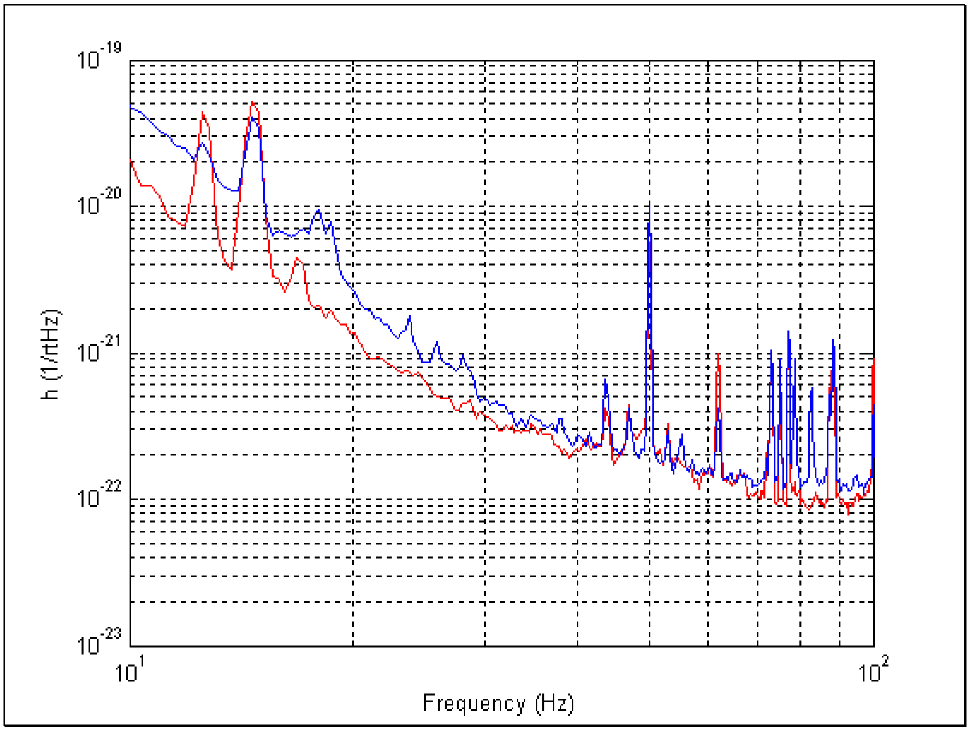


Figure 8 Virgo Sensitivity with (red) and without (blue) shaping filters

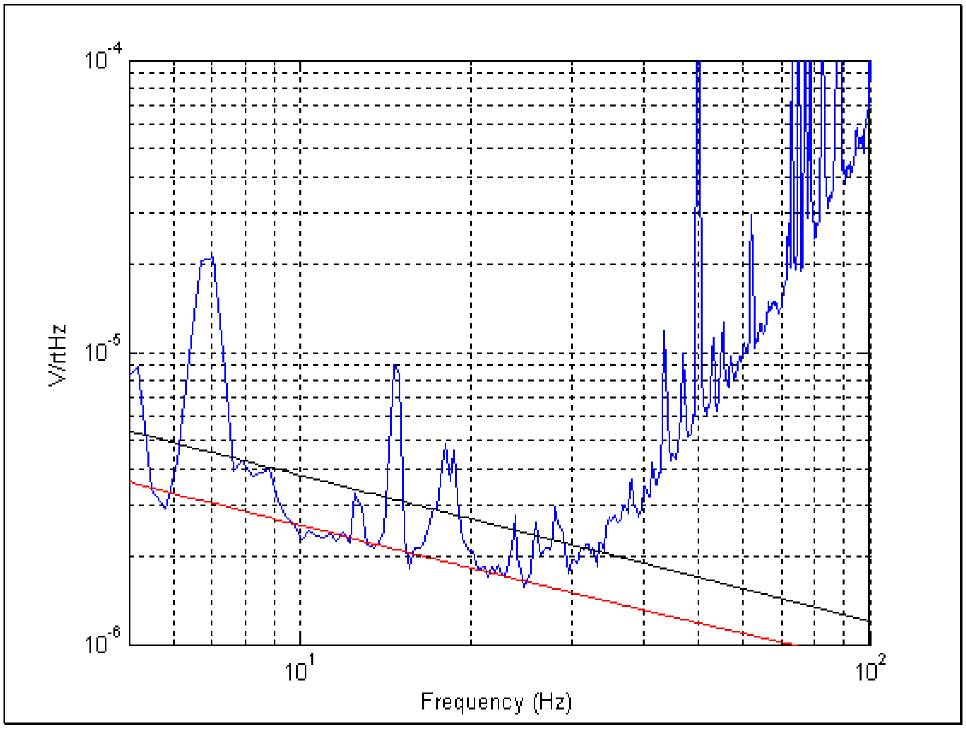


Figure 9. DAC noise (blue) computed starting from measured sensitivity compared with original noise model (black) and with noise model reduced by 30% (red)

3.2 *Dithering*

Once measured the DAC noise using Virgo interferometer, we decided to test dithering technique. For such purpose we switch back on the shaping filters at WE in order to put in evidence the only NE contribution. As dithering signal we used a 5 mV peak sine wave at 353 Hz (a calibration line already available at mirror level) and the effect is shown in the following picture. The left picture is the dark fringe signal while the right plot shows the spectrum of the signal driving the two DACs channels.

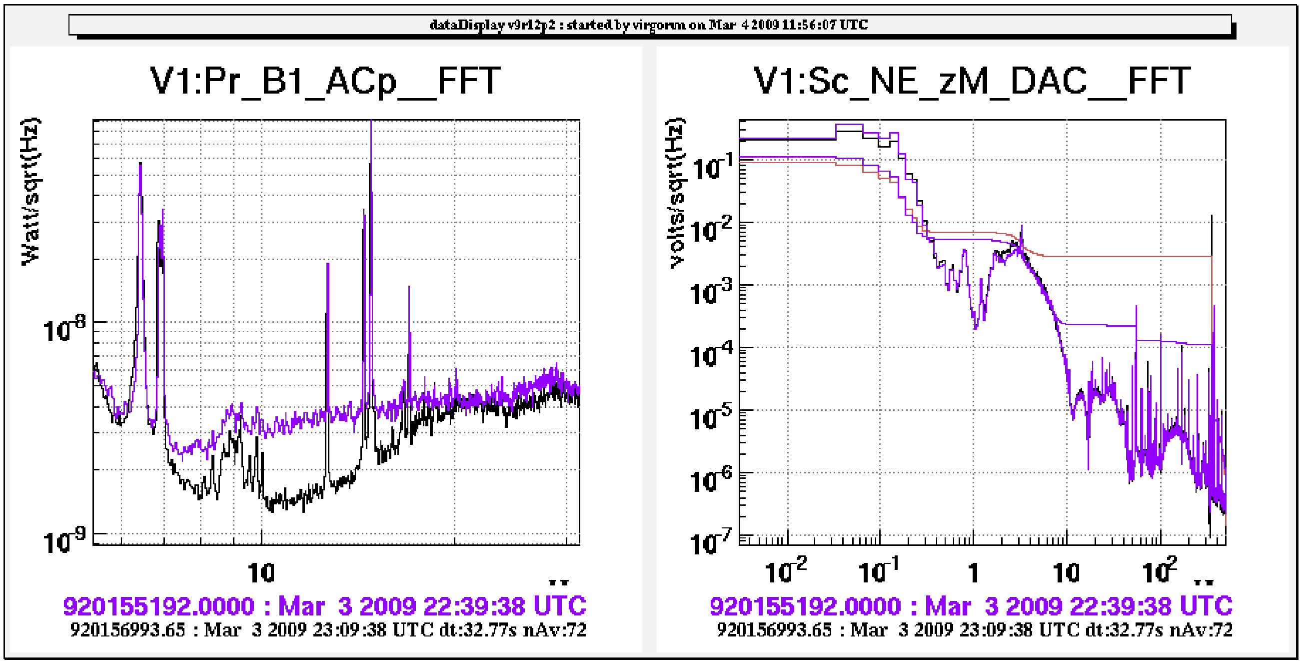


Figure 10 Dithering effect on Virgo dark fringe and DAC signal spectrum

The dithering signal removes the DAC up-conversion effect with results compatible with what obtained last year in laboratory tests (see Figure 6) where we measured a reduction factor equal to 4 at 10 Hz. In this case reduction is only something more than a factor two but we are clearly limited by a different noise source (slopes of two curves are different).

We can also notice in next picture that the difference between signal spectra at WE, shaping filters and no dithering, and at NE, no shaping filters and dithering.

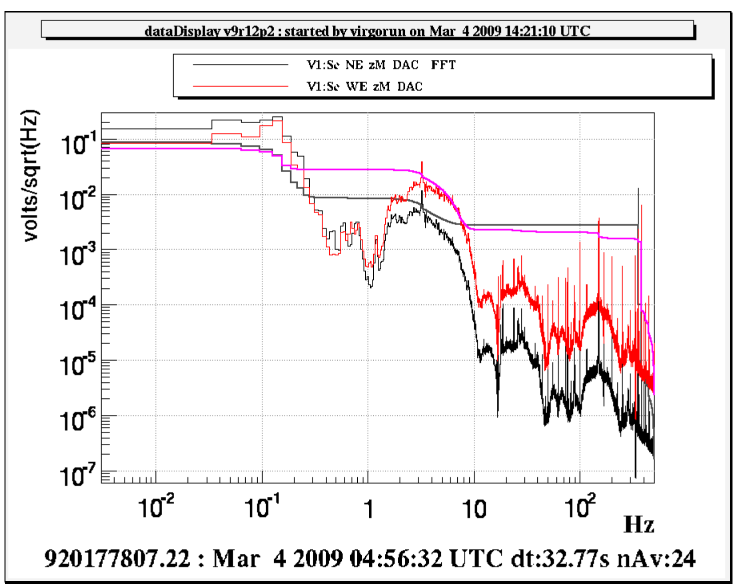


Figure 11 Comparison between DAC signal at WE (shaping filter on, dithering off, red line) and at NE (shaping filter off, dithering on, black line). Both rms values are below 100 mV.

The two spectra have similar rms values at frequencies larger than 10 Hz. The small difference pushes towards the conclusion that there is no need of adding any dithering signal since, thanks to shaping filters, higher frequency components are already available in the DAC signal.

3.3 *Updated DAC Noise Model*

The DAC noise model determined in laboratory lat year can be now updated keeping into account measurement done with Virgo interferometer.

Without signal

$$\tilde{n}_0 \cong \frac{1200}{\sqrt{f}} + 350 \quad \frac{nV}{\sqrt{Hz}}$$

With low-pass signal

$$\tilde{n}_{LP} \cong \frac{8000}{\sqrt{f}} + 350 \quad \frac{nV}{\sqrt{Hz}}$$

With low-pass signal and dithering

$$\tilde{n}_D \cong \frac{2500}{\sqrt{f}} + 350 \quad \frac{nV}{\sqrt{Hz}}$$

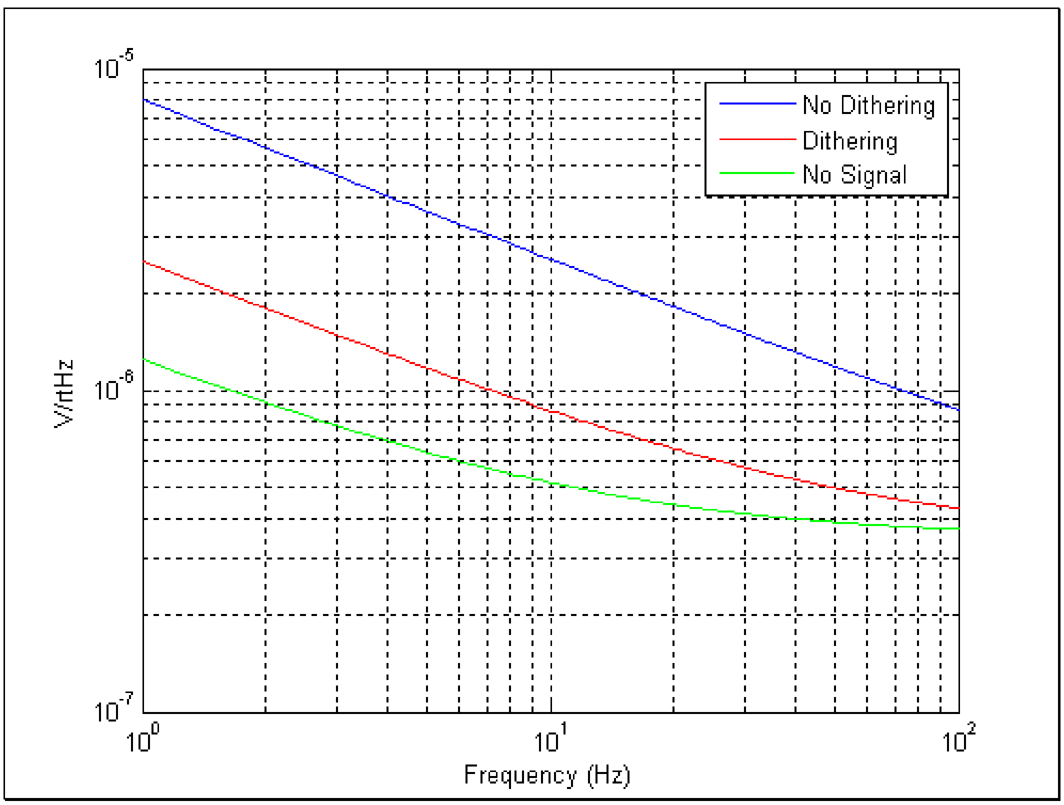


Figure 12 DAC Noise Model

4. EFFECT ON VIRGO SENSITIVITY

Once determined a more accurate model we can update noise budget for what concerns suspension actuators.

4.1 *Long Arms*

4.1.1 Marionette Actuators

All four suspensions (NI NE WI WE) are equipped with shaping filters having as transfer function:

$H_{SMar}(s) = \dfrac{s/\omega_z + 1}{s/\omega_p + 1}$, with pole at about 0.9 Hz and zero at about 9 Hz.

Marionette transfer function (displacement along beam direction in respect with applied force) can be simplified taking into account only the two main modes ad 450 and 980 mHz. The DC gain is assumed to be

$g_{Mar} = 1.7 \cdot 10^{-6} \quad m/V$ (1 coil: applying 1 V at both coil drivers, mirror displacement is 3.4 um)

If z correction forces are applied only at end suspensions, input suspensions marionette coils are driven by a very small signal not producing any up conversion. The power spectrum density (m^2/Hz) of displacements is:

$$\tilde{X}_{NE}(f) = \tilde{X}_{WE}(f) = 2 \cdot g_{Mar}^2 \left|H_{SMaer}(f)\right|^2 \left|H_M(f)\right|^2 N_D(f)$$

$$\tilde{X}_{NI}(f) = \tilde{X}_{WI}(f) = 2 \cdot g_{Mar}^2 \left|H_{SMaer}(f)\right|^2 \left|H_M(f)\right|^2 N_0(f)$$

Total noise due to arms marionette actuators is the sum of the 4 components

$$\begin{aligned}\tilde{X}_{ArmsMar}(f) &= 4 \cdot g_{Mar}^2 \left|H_{SMaer}(f)\right|^2 \left|H_M(f)\right|^2 N_0(f) + 4 \cdot g_{Mar}^2 \left|H_{SMaer}(f)\right|^2 \left|H_M(f)\right|^2 N_D(f) = \\ &= 4 \cdot g_{Mar}^2 \left|H_{SMaer}(f)\right|^2 \left|H_M(f)\right|^2 \cdot \left[N_0(f) + N_D(f)\right]\end{aligned}$$

See Figure 13 in the final paragraph of this section.

4.1.2 Reference Mass Actuators

Input suspensions are equipped with a very large series resistor (6 kOhm) and therefore their noise is negligible compared with terminal towers.

At terminal towers we have a second order shaping filters (2 poles at 0.9 Hz and two zeros at 9 Hz). Mechanical transfer function is the one of a simple pendulum with 600 mHz resonant frequency. DC gain is assumed to be

$g_{mir} = 5.5 \cdot 10^{-6} \quad m/A$ (1 coil: applying 1 A in 2 coils mirror displacement is 11 um)

Output voltage is divided by a series resistor whose value is a function of low noise mode:

Rs = {300,1200,2400,4800} (excluding cable+coil+protection = 20 Ohm)

Reference mass is equipped with 4 coils but only two are currently used ('Up' and 'Down')

$$\tilde{X}_{NE}(f) = \tilde{X}_{WE}(f) = 2 \cdot g_{mir}^2 / R_S^2 \cdot |H_{Smir}(f)|^2 |H_{Mmir}(f)|^2 \tilde{N}_D(f) + 2 \cdot g_{mir}^2 / R_S^2 \cdot |H_{Smir}(f)|^2 |H_{Mmir}(f)|^2 \tilde{N}_0(f) =$$
$$= 2 \cdot g_{mir}^2 / R_S^2 \cdot |H_{Smir}(f)|^2 |H_{Mmir}(f)|^2 \cdot \left[\tilde{N}_0(f) + \tilde{N}_D(f)\right]$$

See Figure 14 in the final paragraph of this section. Only LN1 and LN2 are reported.

4.2 *Plots*

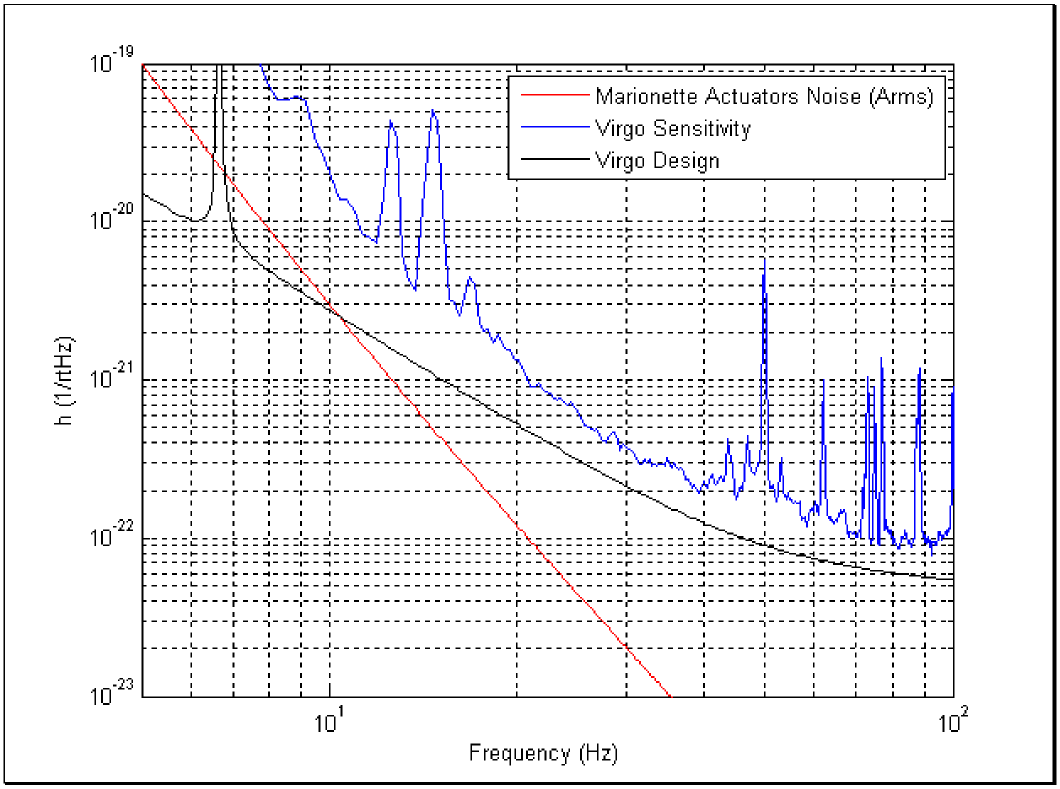


Figure 13 Noise Budget: Arms Marionette Actuators

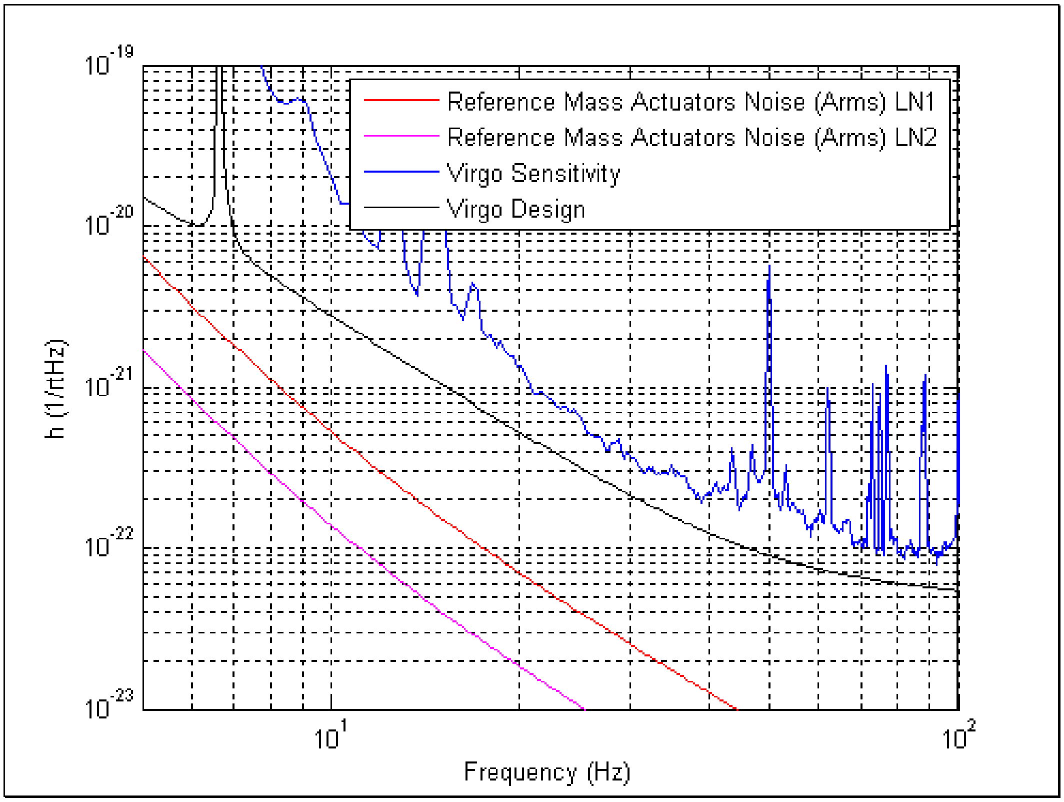


Figure 14 Arms Reference Mass Actuators (LN1 and LN2)

5. CONCLUSIONS

Up conversion (NL noise) is about 8 uV/sqrt(f) and not 12 uV/sqRT(f) as supposed and dithering reduces this noise down to 2.5 uV/sqrt(f).

zCorr spectrum already contains 'dithering' lines but since we can add an high frequency line without any cost we will add such lines. Moreover, where low frequency part of zCorr is applied on marionette (long arms suspensions), up conversion should be negligible even without any dithering.

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