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VIRGO Collaboration

Actuation Noise in Virgo+ and Advanced Virgo

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1. INTRODUCTION

1.1 *Purpose & Scope*

This document presents the noise budget for lower stage actuators for Virgo Science Run no. 2 (VSR2), Virgo+ with monolithic payloads (Virgo+MS) and Advanced Virgo (AdvV) . Main purpose is the preparation of the Virgo+MS total noise budget.

The content of this document was presented to the Virgo Collaboration at the Advanced Virgo meeting held in Cascina on February 4th, 2010 and at the Commissioning/Detector Meeting on February 8th, 2010.

1.2 *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.

AdvV	Advanced Virgo
CD	Coil Driver
DAC	Digital to Analog Converter
DSP	Digital Signal Processor
RD	Reference Document
Virgo+MS	Virgo+ with Monolithic payloads
VSR2	Virgo Science Run No. 2

1.3 *References*

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

[RD1] A.Gennai, Actuators Noise in AdvV, VIR-0093A-10 Presentation to the AdvV Meeting, February 4th, 2010

[RD2] M.Bitossi, A.Gennai, D. Passuello, Low Noise DAC Selection for Advanced Virgo, VIR-0078A-10, January 20th, 2010

A. Gennai, DAC Noise Effect on Virgo Sensitivity, VIR-0006B-09, October 2nd, 2009

[RD3] Gennai, DAC Noise Contribution to Virgo Sensitivity, VIR-0072A-08, June 6th, 2008

[RD4] Gennai, New Coil Driver Measurements, VIR-0010C-08, March 23rd, 2008

[RD5] Gennai, Coil Driver Final Design Document, VIR-SPE-PIS-4900-121, September 30th, 2004

2. VIRGO COIL DRIVER

2.1 *Overview*

In Virgo, mirrors actuation along laser beam direction is performed using 6 electromagnetic actuators. Two horizontal actuators act on Marionette from the Steering Filter (also known as Filter#7) while 4 actuators act directly on mirror from recoil mass (also known as ‘reference’ mass). Starting from position error, the Suspension Control System computes forces using Digital Signal Processors (DSP).

In a magnet-coil actuator, force is proportional to the current flowing in the coil. The Coil Driver (CD) is the electronic device that converts the voltage at the output of the Digital to Analog Converter (DAC) into a current flowing into the coil.

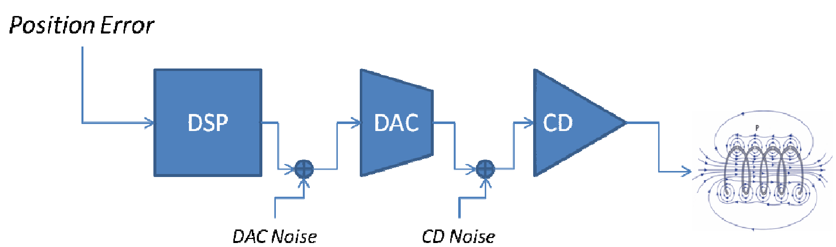


Figure 1 Sketch of the control chain

New Coil Drivers, currently installed at terminal north and west suspensions, have a voltage to current conversion factor that is remotely selectable with a smooth transition from one operation mode to the next one. Five are the available operational modes: HIGHPOWER, used during cavities lock acquisition phase, and LOWNOISE1 to LOWNOISE4 used during linear regime. Further details on coil drivers and their operational modes can be found in [RD4] and [RD5].

2.2 *Coil Driver Noise*

Coil Driver noise can be evaluated using an accurate PSPICE simulation and a comparison with measured values (see [RD4]). The following picture shows the coil driver schematic used in simulation. Three distinct blocks put in evidence the input differential stage, the noise shaping filter and the series resistor. Changing operating mode we simply change the value of the series resistor. Monitoring network is reported only to keep into account of its noise contribution. Shaping filter shown corresponds to the second order filter (two poles – two zeros) we are using in the installed coil driver. Actual design foresees the possibility to implement filter with order ranging from 0 (no filter) to 5th.

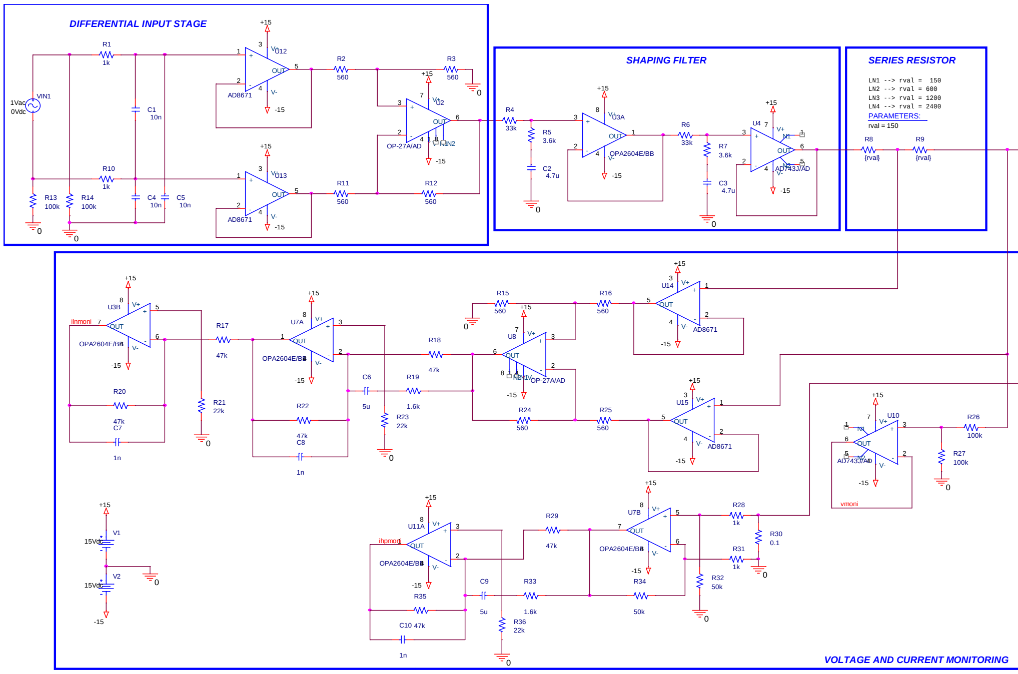


Figure 2 Coil Driver Schematic

Noise refereed to the output of the coil driver, expressed in Ampere/sqrt(Hz) is of course a function of the operating mode since changing operating mode we change the voltage to current conversion factor.

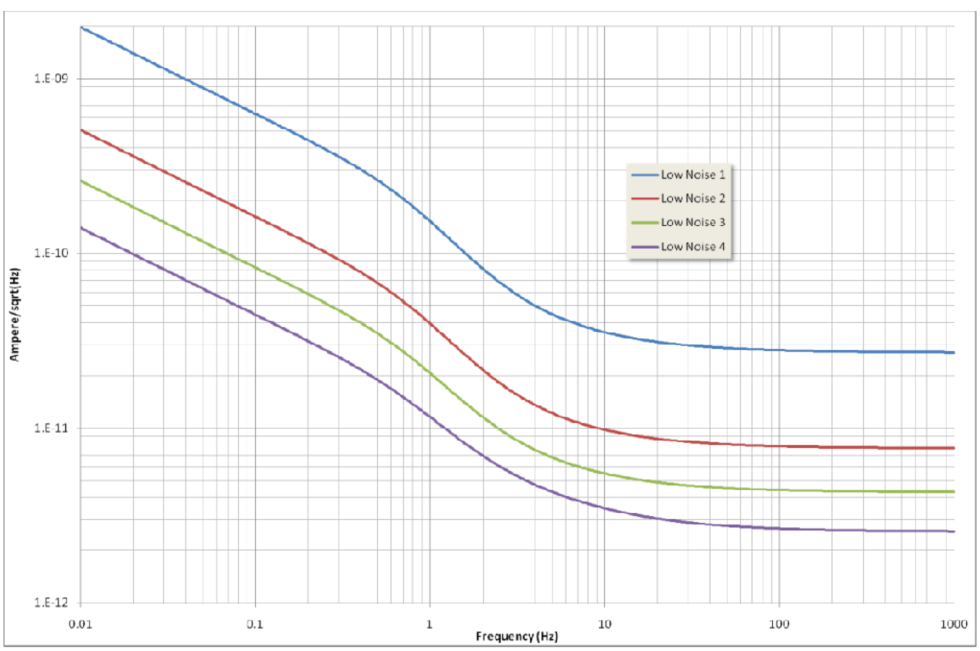


Figure 3 Coil Driver Output Noise

Due to the second order low pass filter, referring the Coil Driver noise to its input, we obtain the following picture where at frequencies bigger than about 10 Hz noise is ‘amplified’ by the filter itself. We should in fact notice that voltage gain (from differential stage input to shaping filter output) is lower or equal to one and therefore input stage noise is not dominant in respect with shaping filter noise.

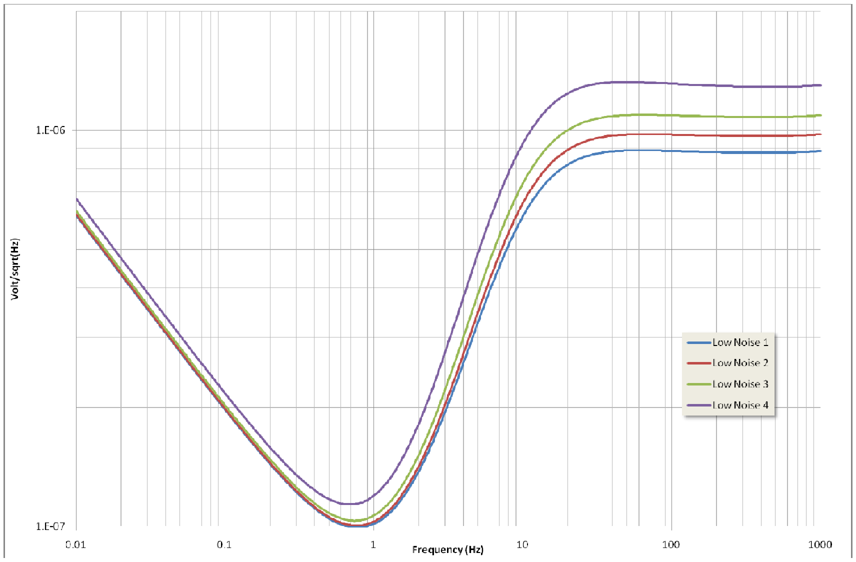


Figure 4 Input Referred Noise

For better understanding, we can compare output and input noise using a first order and a second order filter.

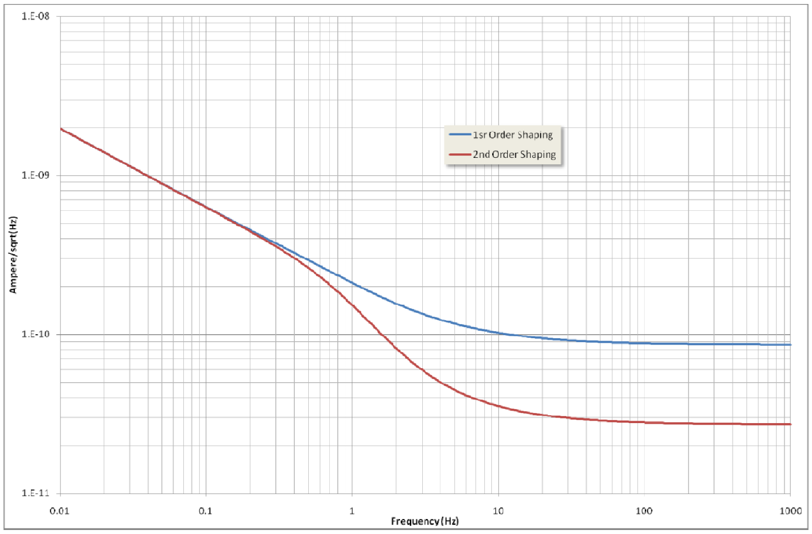


Figure 5 Low Noise 1 Output Noise: Comparison between 1st order and 2nd order shaping filter

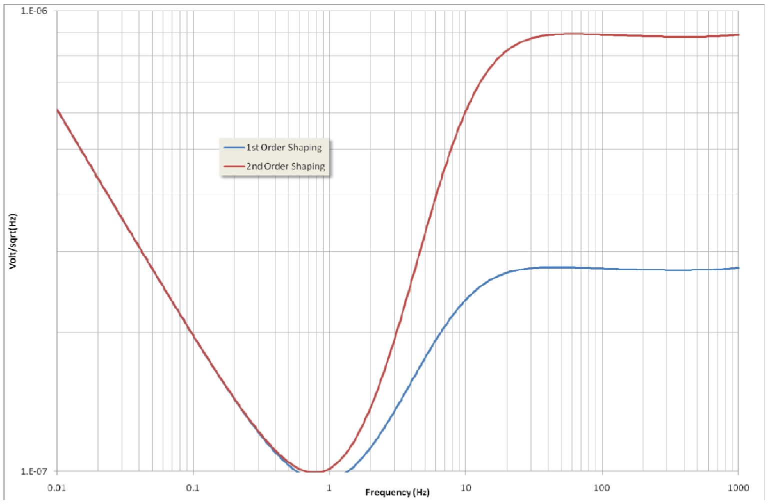


Figure 6 Low Noise 1 Input Referred Noise: Comparison between 1st order and 2nd order shaping filter. High frequency (1 kHz) value is about 270 nV/sqrt(Hz). Completely removing shaping filters that value drops down to about 12 nV/sqrt(Hz) while low frequency (below 1 Hz) behaviour remains unchanged[1].

2.3 *DAC Noise*

Once coil driver noise is known we can evaluate the contribution of DAC noise both at CD input and output. In the following two plots we used the DAC noise measured as described in [RD2]A and [RD3]. With filters in use during VSR2 (where only LOWNOISE1 was used) DAC contribution equals CD contribution between 20 and 30 Hz.

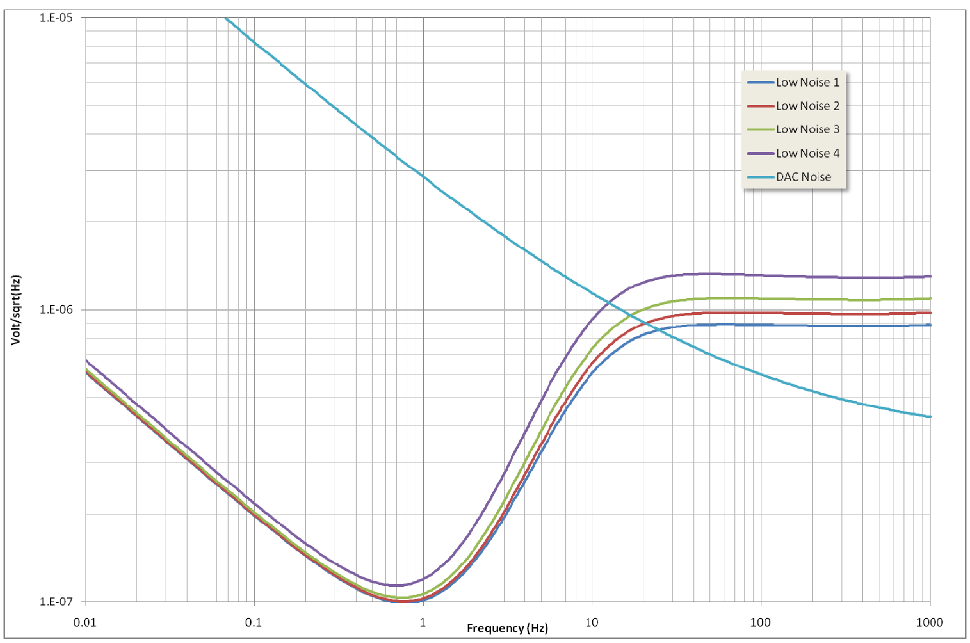


Figure 7 Input Referred Noise superposed to DAC noise estimate

[1] Removing the shaping filter block, we gain a factor ~10 due to filter transfer function. Total noise is furthermore reduced by the amount of noise introduced by the shaping filter operational amplifiers and resistors.

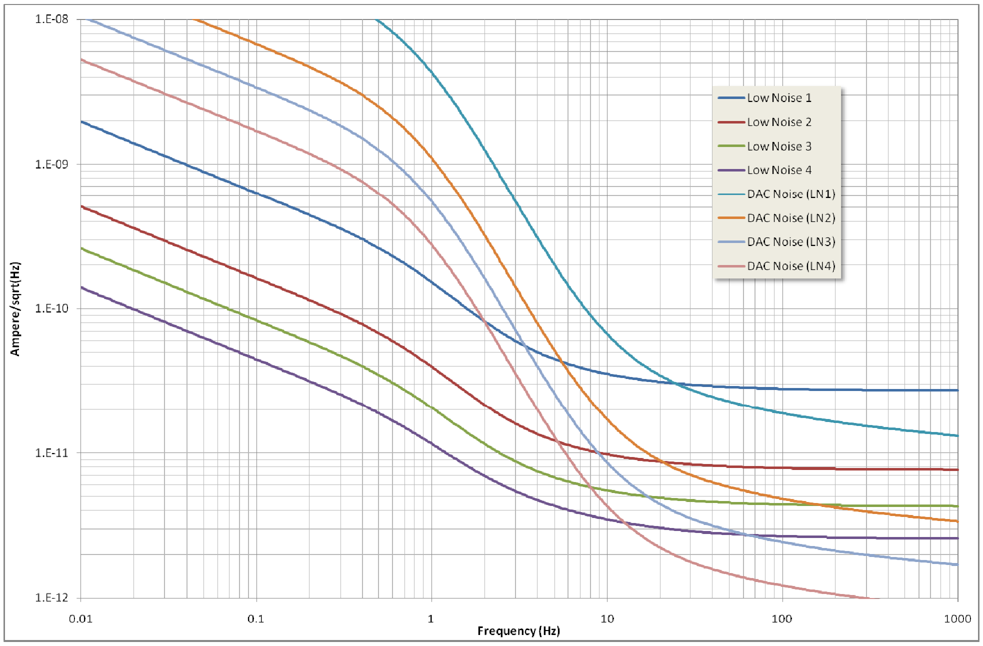


Figure 8 Output Noise: Coil Driver and DAC Contribution

2.3.1 Old Coil Driver

It is worth reminding here that during VSR2 we used old coil drivers for Filter #7 – Marionette actuators. Behaviour is different from the one described up to now and applicable to new coil drivers (acting in VSR2 on mirror only). Voltage gain is 2 while input referred noise is about 100 nV/sqrt(Hz), almost flat above 1 Hz. At its input there is a first order shaping filter (pole at 0.9 Hz, zero at 9 Hz). Output noise, including DAC noise contribution, is shown in the following picture.

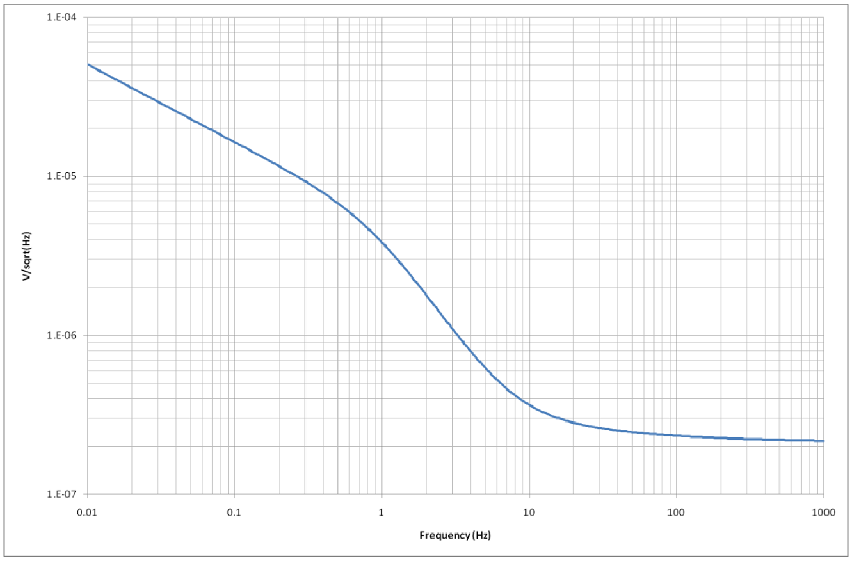
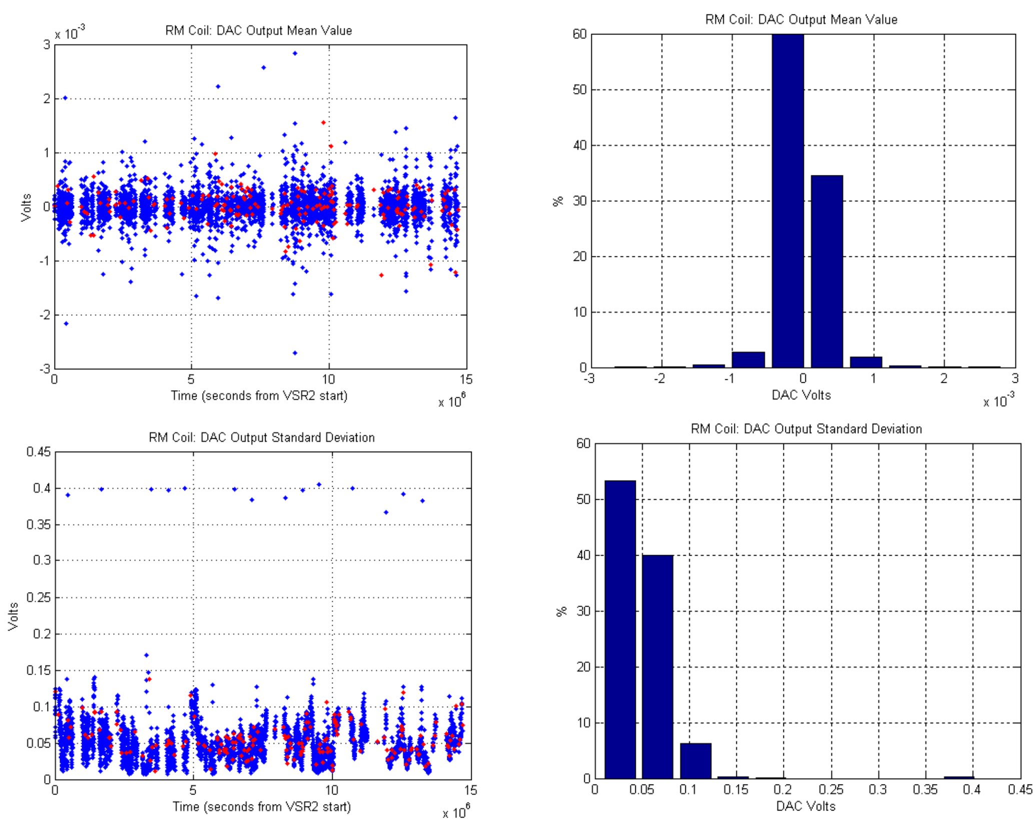


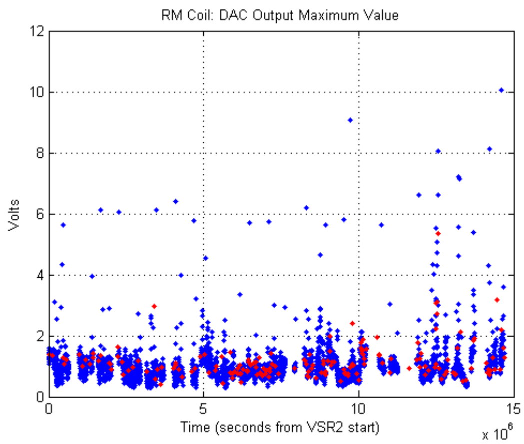
Figure 9 Old Coil Driver Output Noise (DAC contribution included)

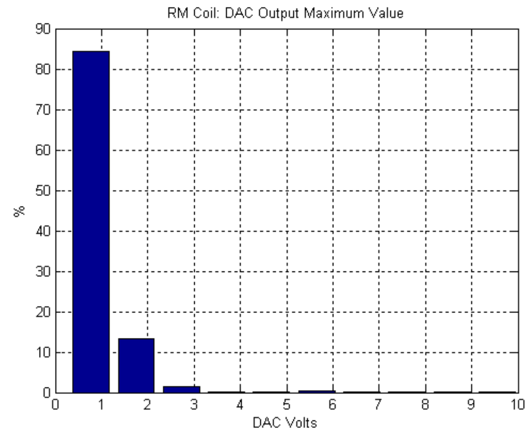
3. SIGNALS DYNAMIC

Once the noise is known we have to decide what should be the equivalent displacement. Adding a series resistor to the coil we can reduce the noise equivalent displacement but of course in this way we also limit the maximum displacement we can achieve. A correct evaluation of required dynamical range is therefore important for selecting a proper operational mode. For this purpose we analyzed the first 231 science mode segments during VSR2 (almost all segments). A Science Mode segment is the time interval in which Virgo interferometer is acquiring scientific data and corresponds to more than 80% of the total time. Each Science Mode segment was than split into 30 minutes sub-segments and for each segment we computed mean value, standard deviation and absolute maximum. Analysis was performed only for end mirrors since input mirrors are not driven along the beam direction and other mirrors have a negligible contribution to total noise.

3.1 *Reference Mass – Mirror Actuators*







As we can clearly see from last two plots, we used only a small fraction of available dynamical range. We could in fact operate in LOWNOISE2 mode (4x series resistor) for about 95% of science mode time and in LOWNOISE3 mode (8x series resistor) for more than 80% of science mode time.

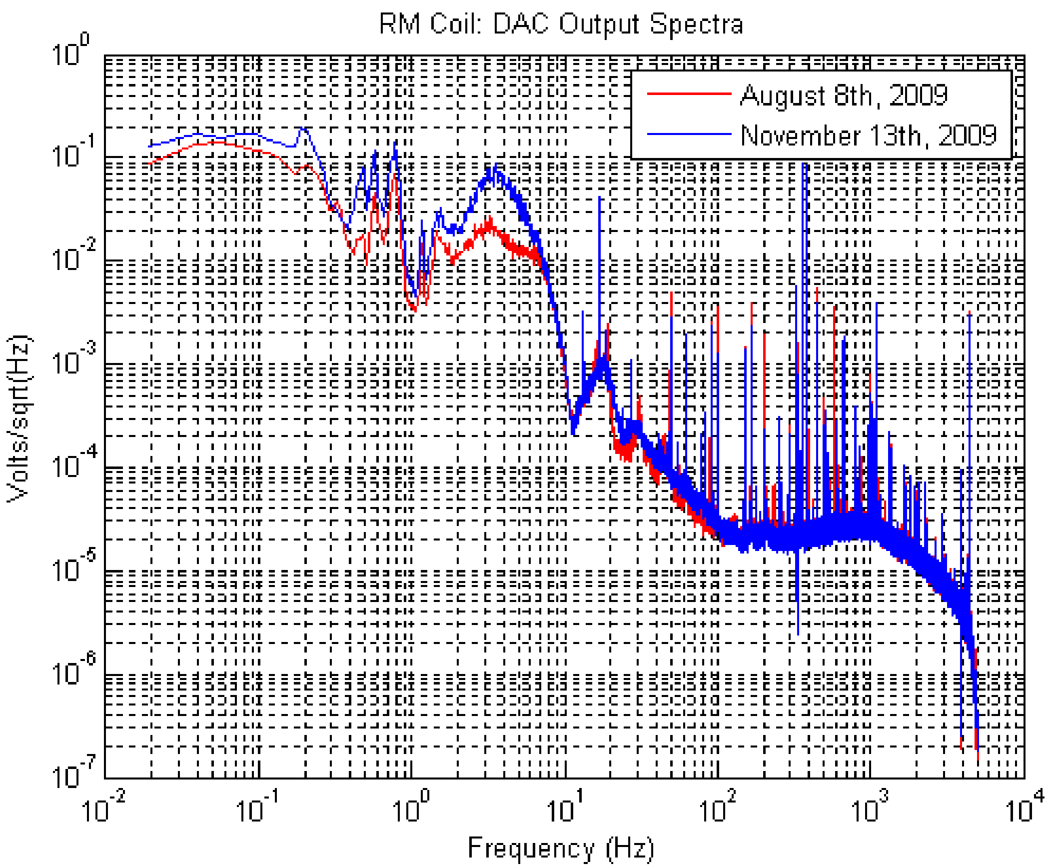
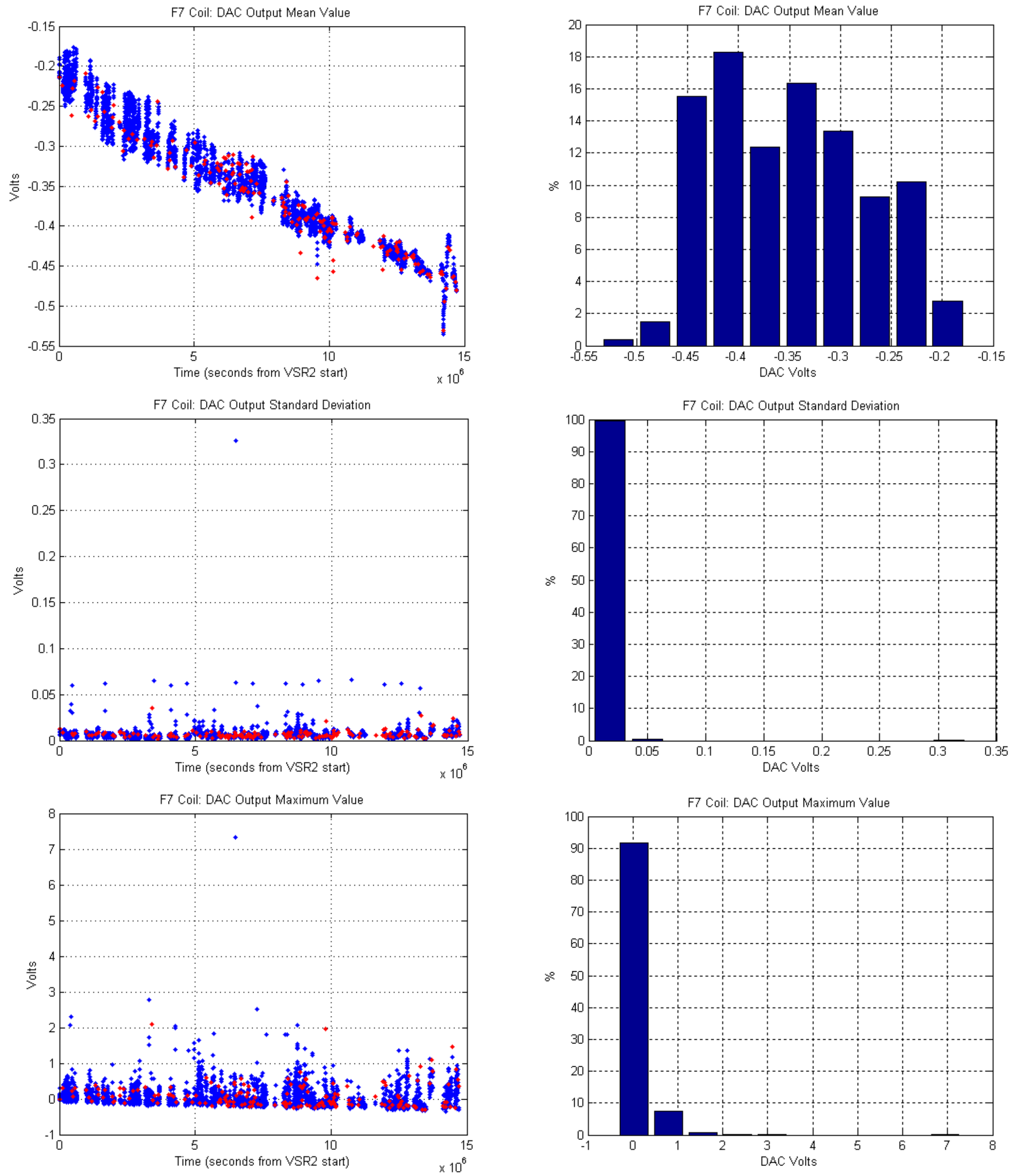


Figure 10 Reference Mass - Mirror Actuators. The two plotted lines correspond to two different period of time

3.2 *Filter #7 - Marionette*



In this case we can see that we could operate for 99% of science mode time inserting a 5x series resistor.

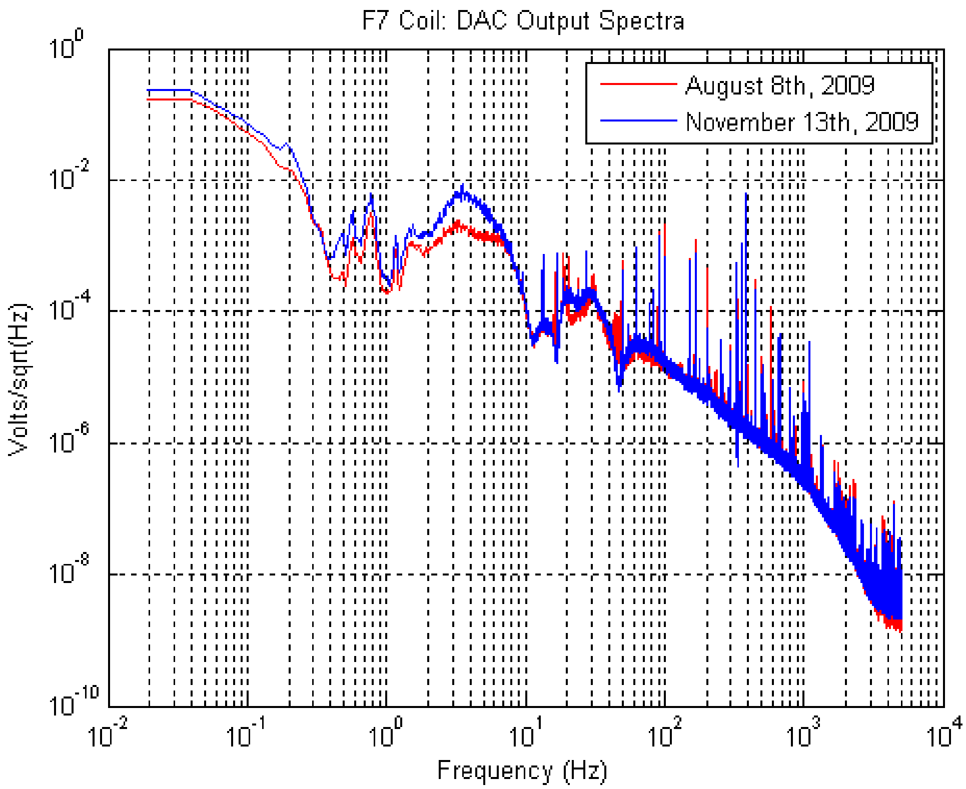


Figure 11 Filter#7-Marionette Actuators

Looking at DAC output spectra and comparing with the spectra of reference mass coils (Figure 10) we notice that at F7 coils we can have a further improvement increasing low pass filter order (from 1st to 2nd)

4. PAYLOAD TRANSFER FUNCTIONS

For a correct evaluation of actuation noise contribution we use a model of the payload transfer function.

4.1 *Reference Mass – Mirror*

DC displacement is about 5.5 um/A per coil. For example, using two coils as we did in VSR1 and VSR2 we have 11 um/A DC displacement. Mechanical transfer function is the classical single pendulum response with 0.6 Hz as resonant factor and a quality factor large enough to be assumed equal to infinity.

Above resonant frequency (0.6 Hz), mechanical transfer function is therefore

$|H_{RM}(f > f_0)| \cong 5.5 \times 10^{-6} \frac{f_0^2}{f^2} \cong \frac{2\times 10^{-6}}{f^2}\ m/A$ (acting with 1 coil)

4.2 *Filter #7 – Marionette*

Acting from filter #7 onto Marionette, DC displacement is about 1.7 um/V_{DAC} (using a single coil and old coil drivers) corresponding to 0.85 um/V_{coil} or, assuming the coil impedance to have a real part equal to 16 Ohm, 7 um/A. Mechanical transfer function is equivalent to a double pendulum response having f_1=0.46 Hz and f_2=0.98 Hz as resonant frequencies:

$$|H_M(f > f_2)| \cong 0.85 \times 10^{-6} \frac{f_1^2 f_2^2}{f^4} \cong \frac{1.75\times10^{-7}}{f^4} \text{ m/V (with 1 horizontal coil)}$$

or, equivalently

$$|H_M(f > f_2)| \cong 7 \times 10^{-6} \frac{f_1^2 f_2^2}{f^4} \cong \frac{1.4\times10^{-6}}{f^4} \text{ m/A (with 1 horizontal coil)}$$

5. NOISE BUDGET

5.1 *VSR2 Noise Budget*

In VSR2 we used the following configuration: new coil drivers in LOWNOISE1 mode acting on two coils at NE and WE. NI and WI mirrors, due to the extremely large value used for series resistors (6 kOhm), give a negligible contribution to long arms actuator noise.

Coil driver used for Filter #7-Marionette actuators is the old one with a first order shaping filter.

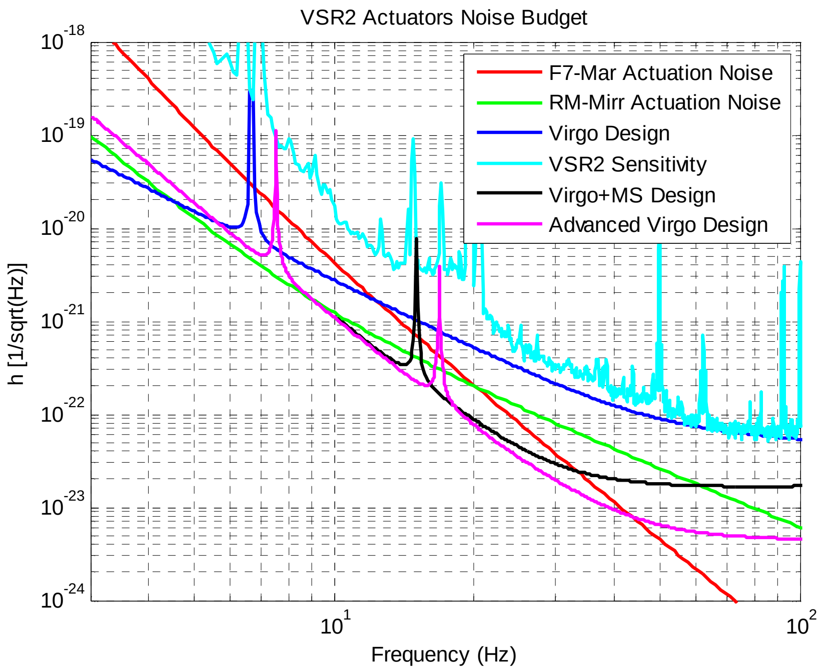


Figure 12 VSR2 Actuators Noise Budget (Long Arms only)

5.2 *Virgo+ MS Noise Budget*

After monolithic payloads installation, thermal noise contribution to Virgo sensitivity will drop down. Meeting requirement for actuation noise is possible using the LOWNOISE2 mode at reference mass level and adding a 5x series resistor to marionette actuators.

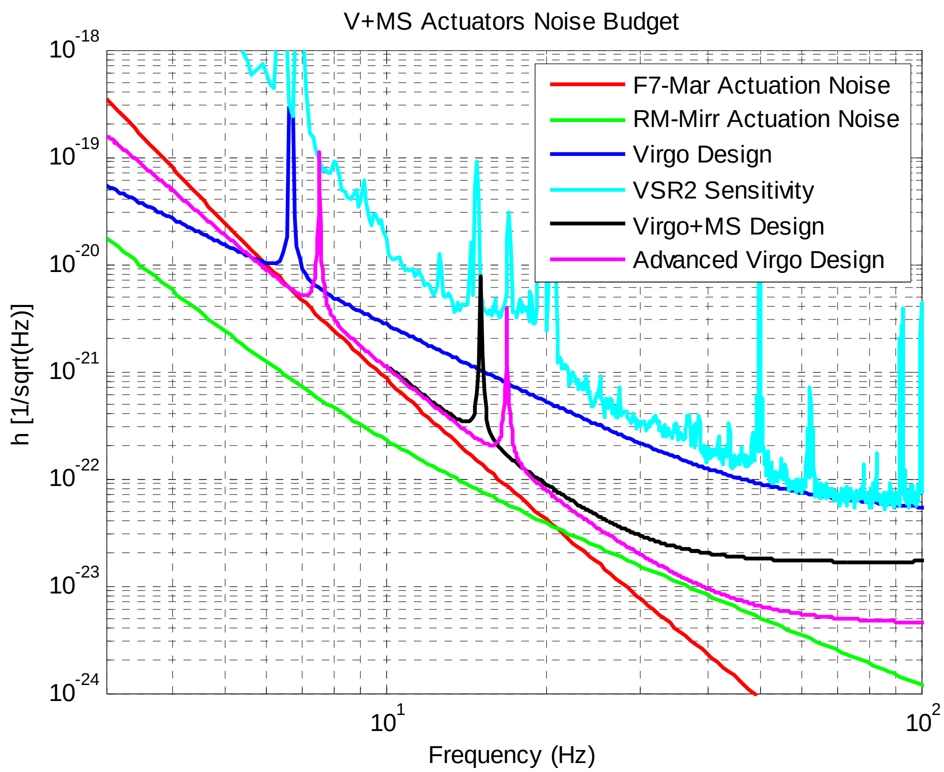


Figure 13 Virgo+ Monolithic Payloads Actuators Noise (Long Arms only)

To be noticed that further improvements are possible implanting second order filter at Filter#7-Marionette level and switching to LOWNOISE3 mode at reference mass – marionette level. Furthermore acting on more coils (at present we use only 2 of the 4 coils available) and/or more mirrors (at present we act only on end mirrors and we do not use input mirrors for cavities longitudinal lock).

5.3 *Advanced Virgo*

With Advanced Virgo we will be able to take advantage from new DAC. Recent measurements on evaluation boards show that new DAC performances are much better than old converters (see [RD2]) with a gain of a factor about 20 at 10 Hz.

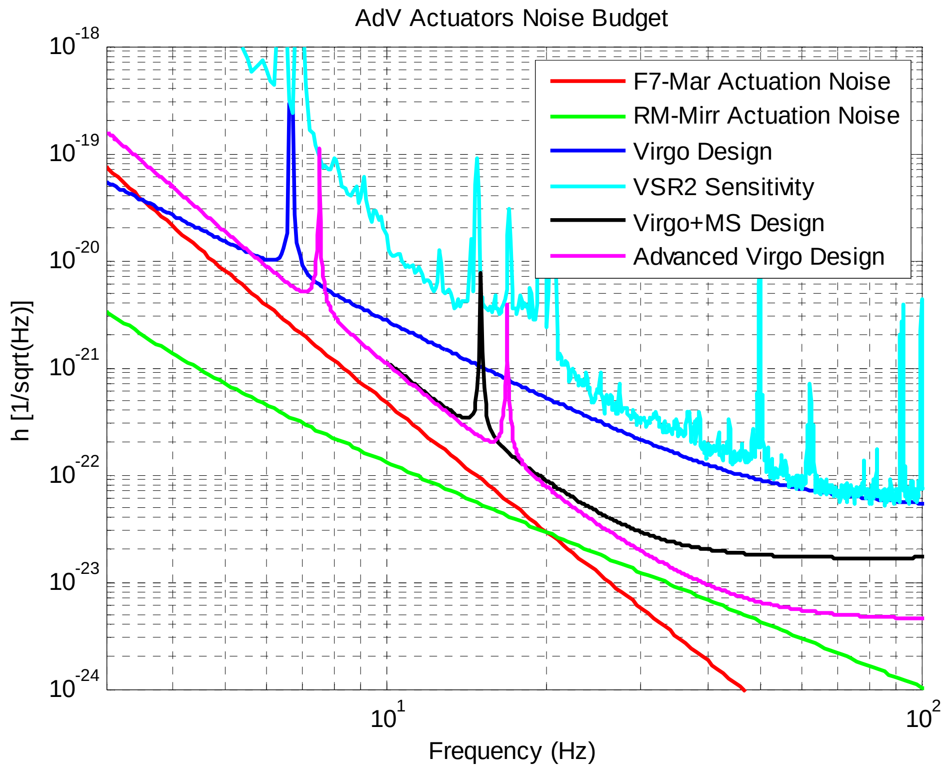


Figure 14 Advanced Virgo Actuators Noise (Long Arms only)

Moving from old DAC to new one we will reduce DAC noise by about a factor 20 at 10 Hz. As it can be noticed comparing Figure 13 and Figure 14, sensitivity will not improve by the same amount since DAC noise is not the limiting noise (see Chapter 2.3). The actual gain is at low-pass filter level where we could guarantee the same performances using a 1st order filter

Increased linearity will allow achieving required performances without dithering (either ‘natural’ or ‘artificial’)

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