Experimental evidence for an Optical Spring

Experimental set up (LFF)

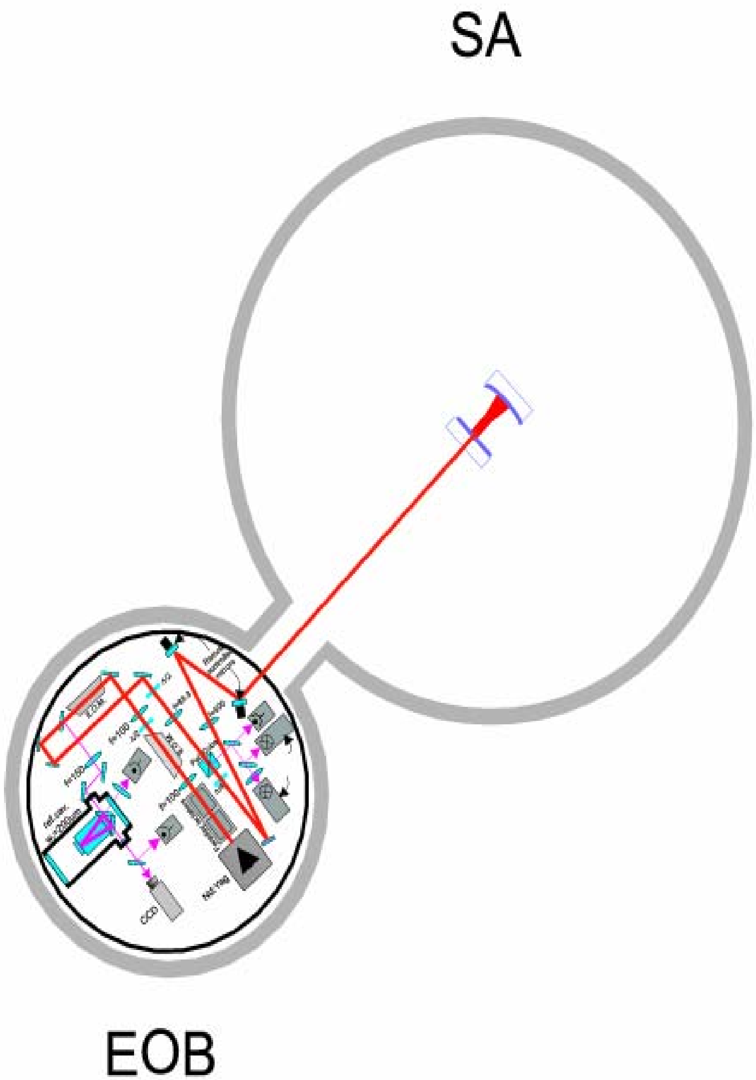
The data and a simple model

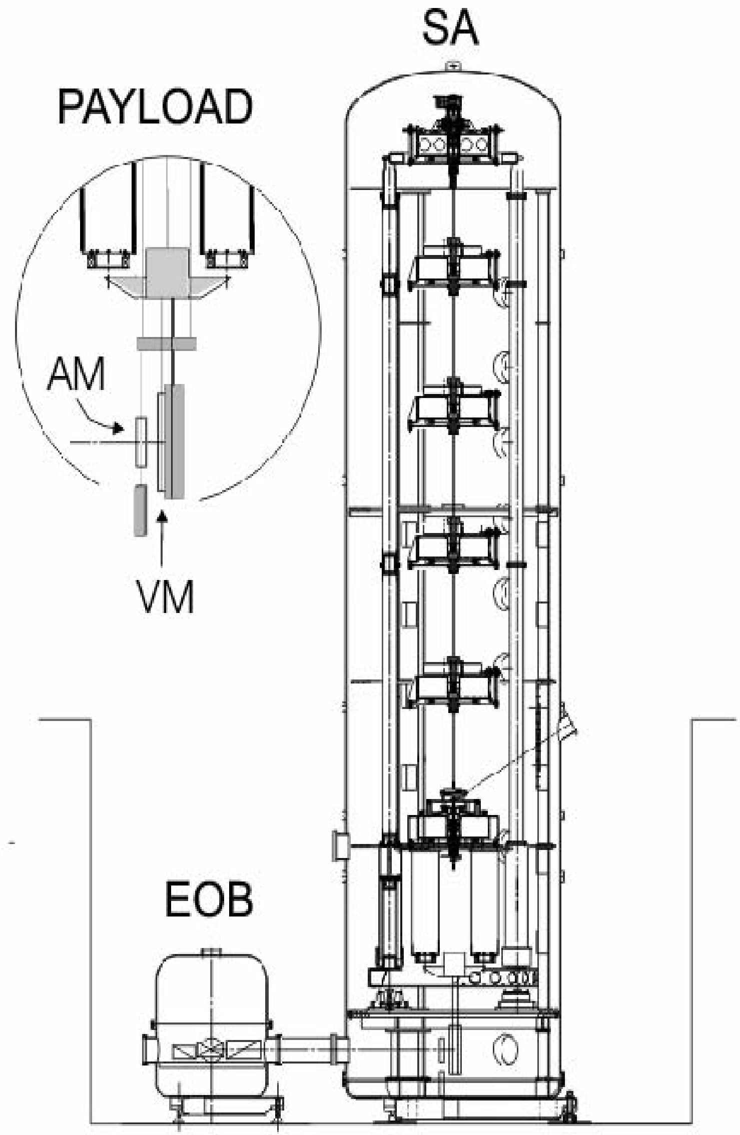
Evidence of the optical spring, linear data

Evidence of the optical spring in the non linear data

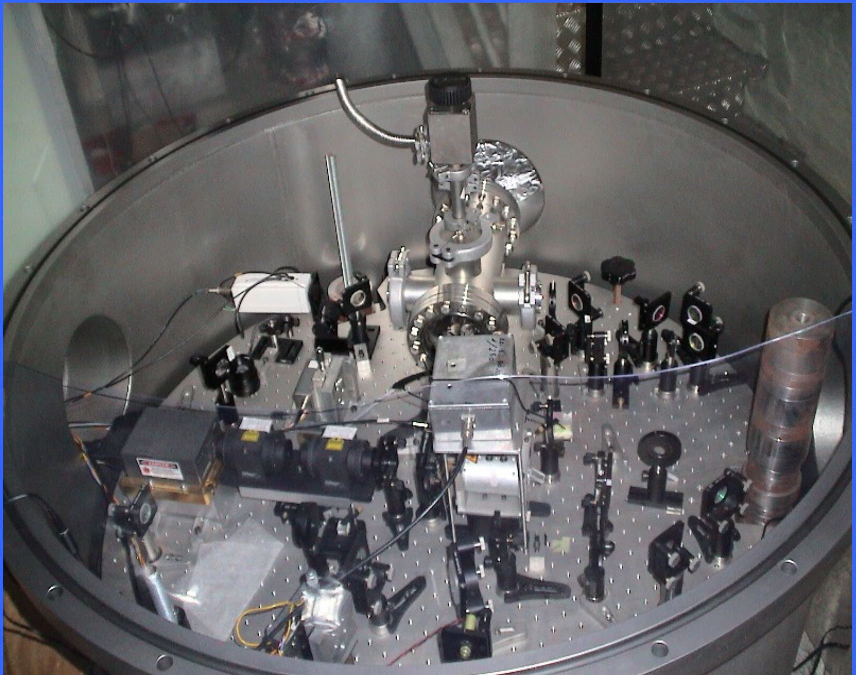
The Low Frequency Facility

- The LFF is an experimental set up, built using the SA prototype (Pisa Fi-Urb Na Roma1, INFN Comm. II), located inside the INFN Pisa section (S. Piero a Grado, Pisa)
- Measurement of the thermal noise spectrum at 10 Hz and tests of the SA performances at low frequency


SA
EOB


SA
PAYLOAD
AM
VM
EOB





LFF papers

M. Bernardini et al. “Plan Parallel mirrors Fabry-Perot cavity to improve the Virgo superattenuators”, Phys. Lett. A* 243 (1998) 187-194.

A. Di Virgilio et al. “Transmittivity profile of high finesse PPFL cavity”Optics Communication, 162 (1999) 267-279

A. Di Virgilio et al “Reflected wave-front sensing signal computation and experimental digital control of a plane-concave cavity” Il Nuovo Cimento- Vol 114 B, N. 10-Ottobre 1999, pp 1197-1212

G. Cella et al. Suspension for the Low Frequency Facility Physics Letters A 266 (2000) 1-10

Di Virgilio “The Earth-based large interferometer Virgo and the Low Frequency Facility Gravitational Waves”, edited by I. Ciufolini, V. Gorini, U. Moschella and P. Fre', Institute of Physics Publishing, Bristol and Philadelphia

F. Benabid et al.”The Low Frequency Facility R&D experiment of the Virgo project” J. Opt. B: Quantum Semiclass. Opt. 2 (2000), 1-7

G. Ballardin,et al: Measurement of the transfer function of the steering filter of Virgo SuperAttenuator” Rev.Sci.Instrum, 72 (2001) 3635

A. Di Virgilio et al. “A Fabry-Perot cavity used as a speed-meter” Phys Lett. A, 313 (2002), 1-9

A. Di Virgilio et al. “Sensitivity of the LFF experiment around 10 Hz”, Phys. Lett A. 322 (2004) 1-9

L. Bracci et al,” Status of the LFF experiment” Class. Quant. Gravity 19 (2002), 1675-1682.

A.Di Virgilio et al “Status report of the LFF experiment”, Virgo R&D, Phys. Lett. A, 318 (2002), 3,199-204

A. Di Virgilio et al, “First results of the LFF experiment”, Class. Quantum Grav.. 21 (2004), S-1099-S1106

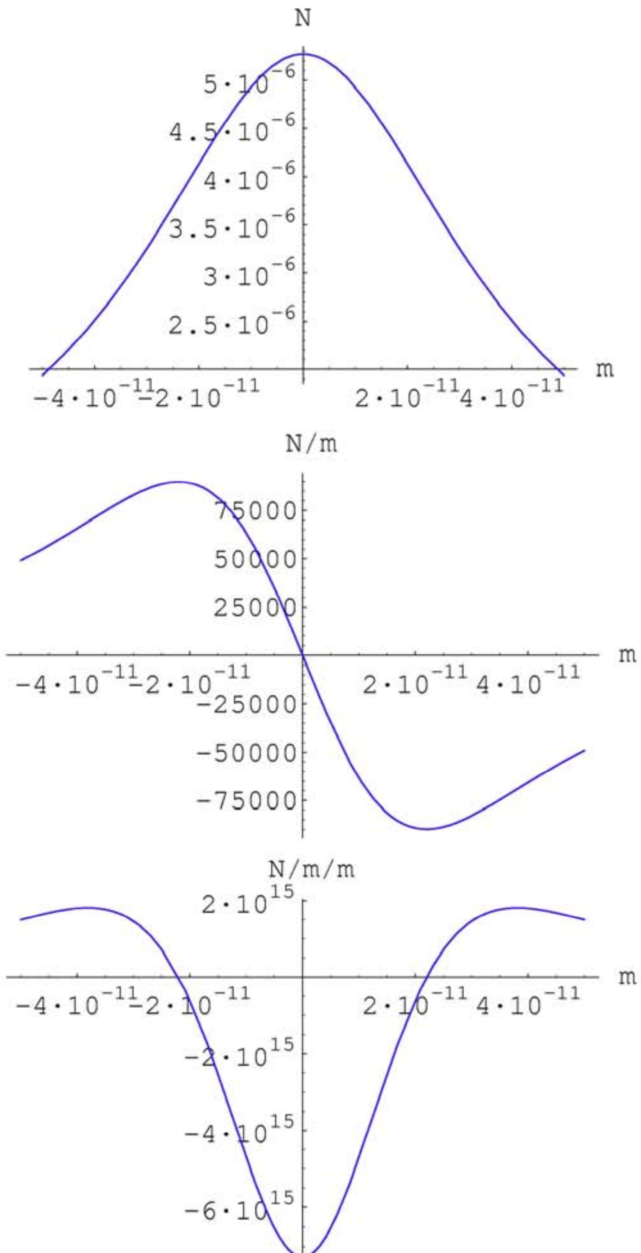
A. Di Virgilio et al. “Sensitivity of the LFF experiment around 10 Hz”, Phys. Lett. A 322 (2004) 1-9

A. Di Virgilio et al. “Considerations on collected data with the LFF experiment” Journal of Phys., accepted December 2005

Di Virgilio et al. “Experimental evidence for an optical spring” Phys. Rev. A. (May 2006) ?

G. Cella et al. “Optical response of s misaligned and suspended FP cavity” Phys. Rev. A (May 2006)

A. Di Virgilio et al., “Thermal noise ?”, in preparation



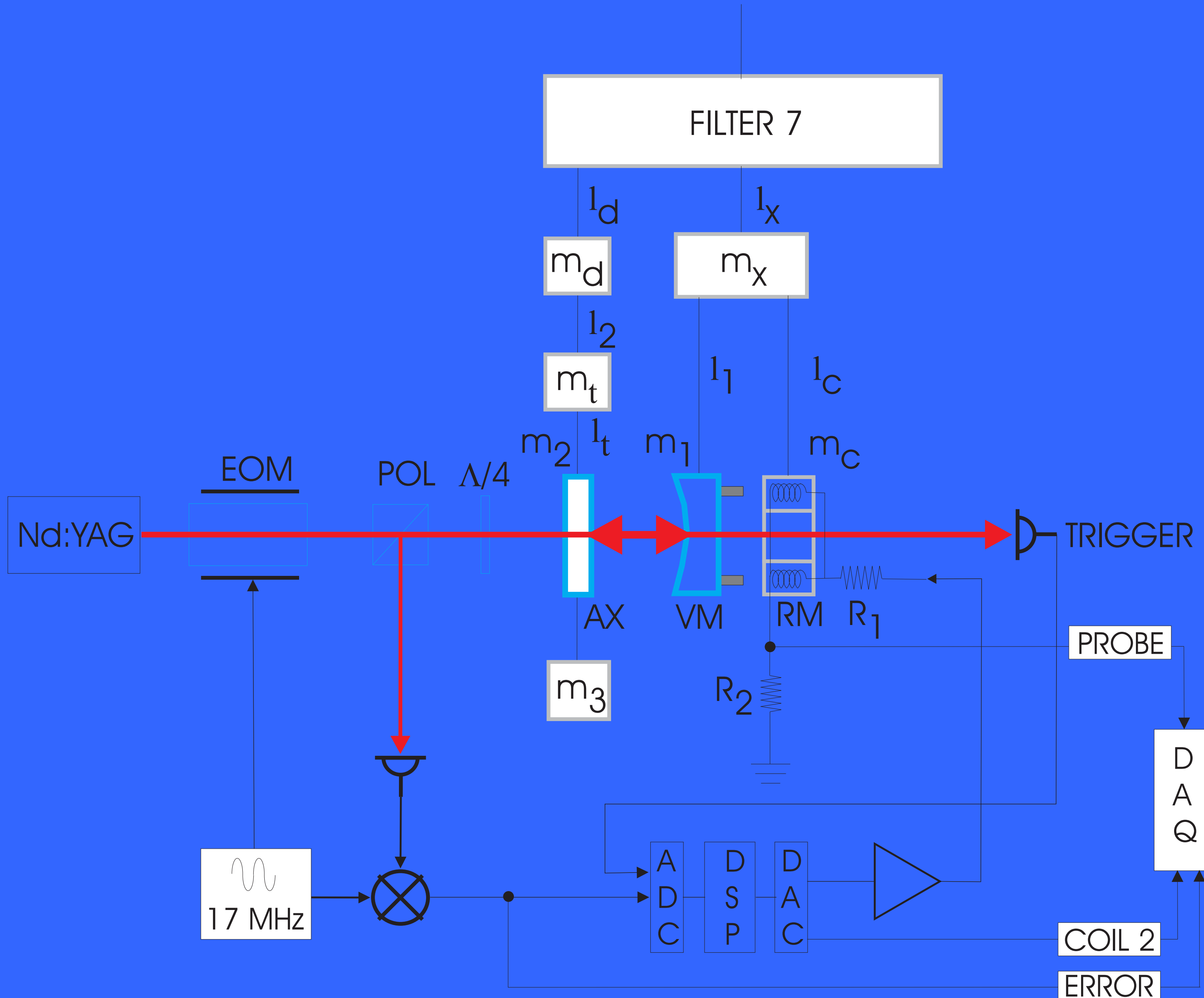
N
5·10^-6
4.5·10^-6
4·10^-6
3.5·10^-6
3·10^-6
2.5·10^-6
m
-4·10^-11
-2·10^-11
2·10^-11
4·10^-11
N/m
75000
50000
25000
-25000
-50000
-75000
m
-4·10^-11
-2·10^-11
2·10^-11
4·10^-11
N/m/m
2·10^15
-2·10^15
-4·10^15
-6·10^15
m
-4·10^-11
-2·10^-11
2·10^-11
4·10^-11

Evidence of the Optical Spring

1) The point of locking has always the same polarity

2) The error signal has an anti-resonance (about 4 Hz) and a broad peak (40-100 Hz)

3) Presence of an-harmonicity

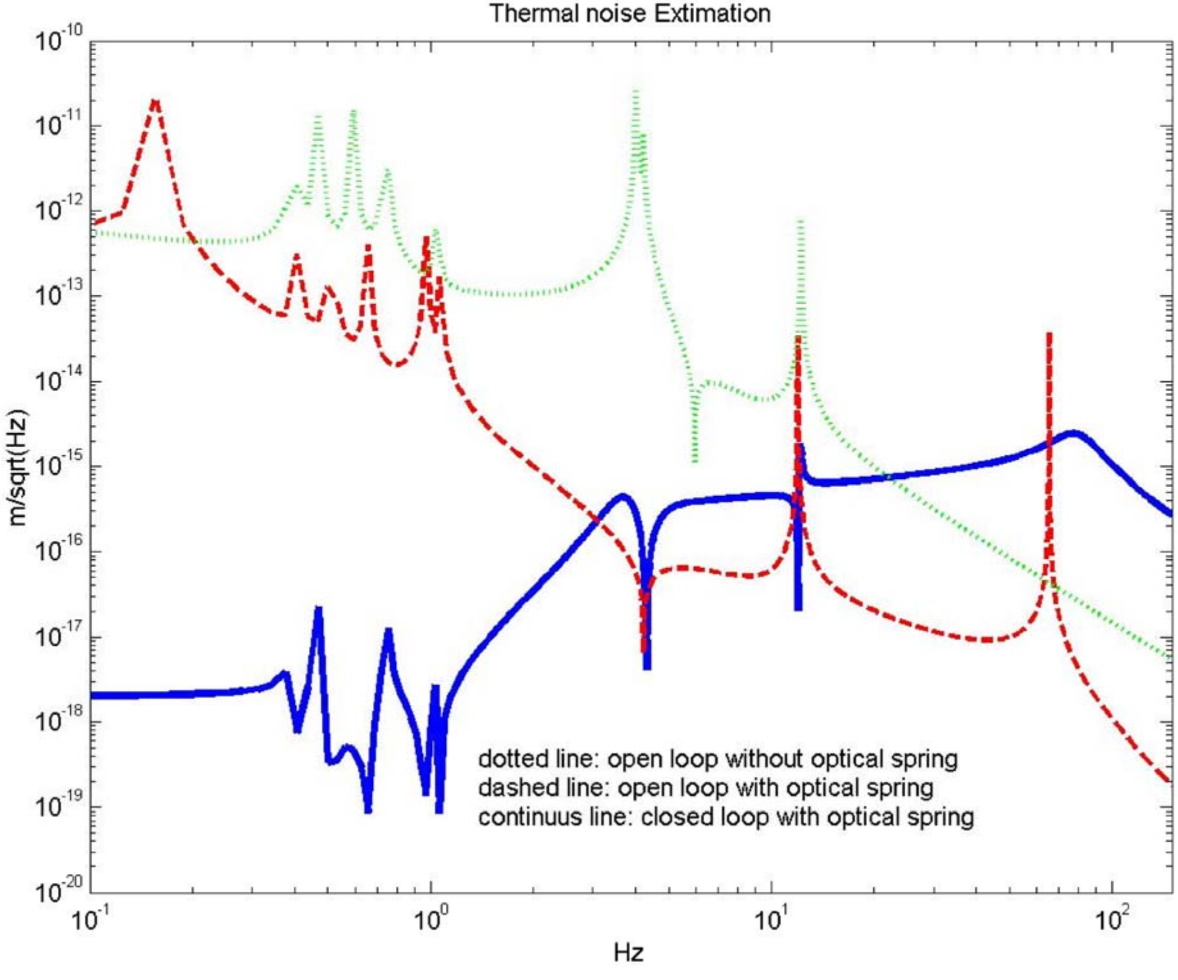


FILTER 7
ld
lx
md
mx
l2
l1
lc
mt
m2
lt
m1
mc
EOM
POL
Λ/4
Nd:YAG
TRIGGER
AX
VM
RM
R1
PROBE
m3
R2
D A Q
ADC
DSP
DAC
17 MHz
COIL 2
ERROR

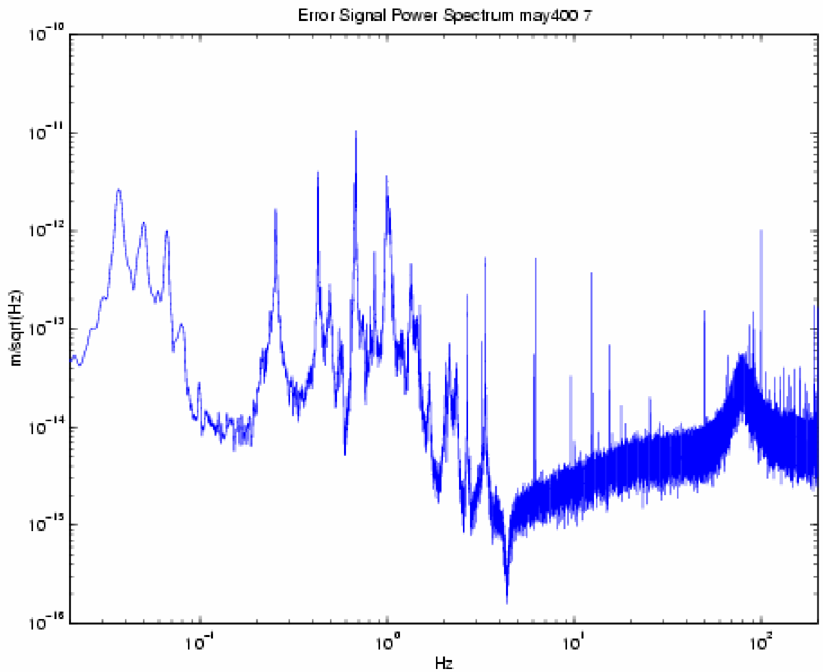
Linear Runs

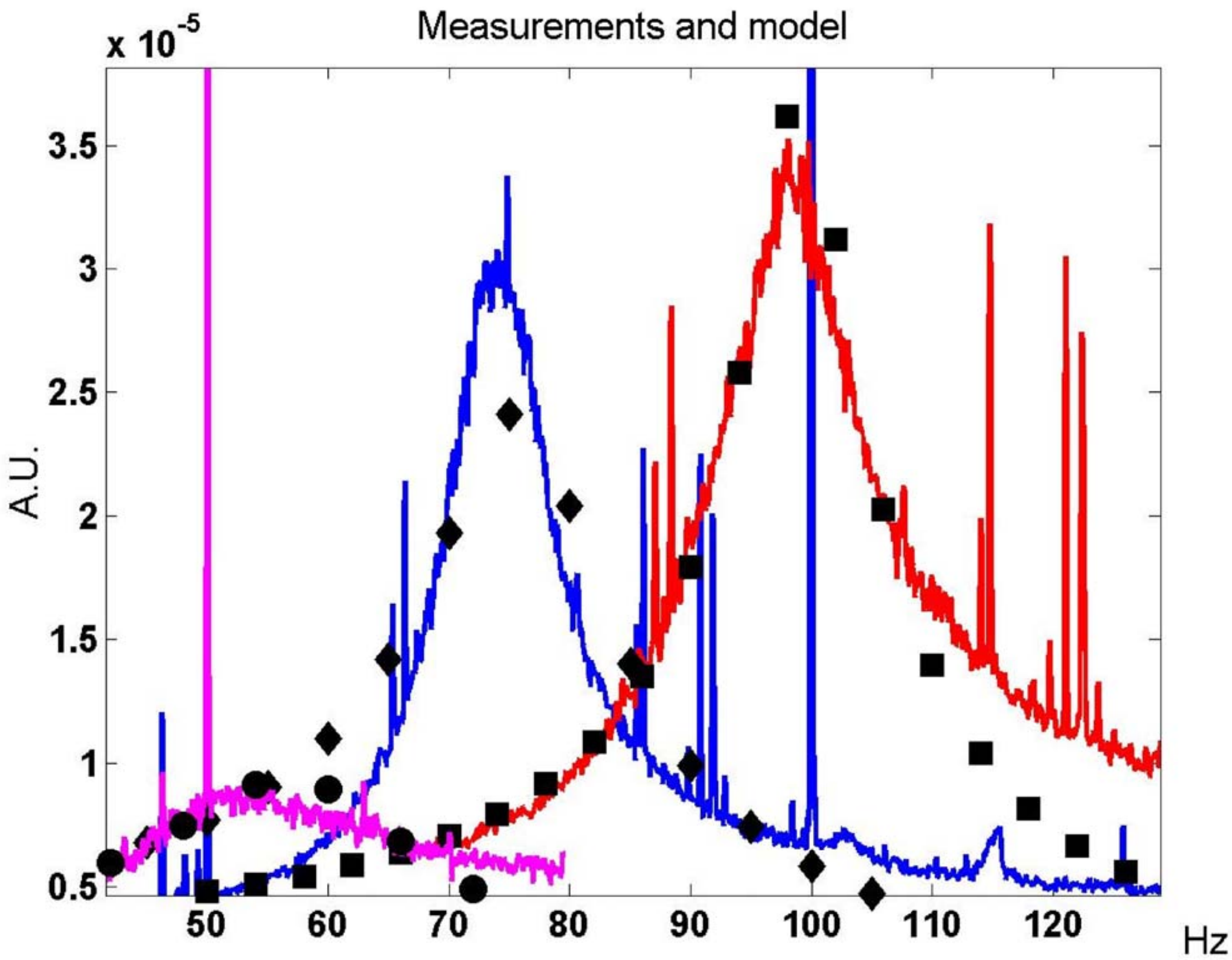
The model (linear case)

- The model consists on a set of differential equations (7), which take into account the all last stage pendulums, and the optical spring as a standard linear one; the mass are considered point-like, and the wires mass-less
- The control loop is taken into account

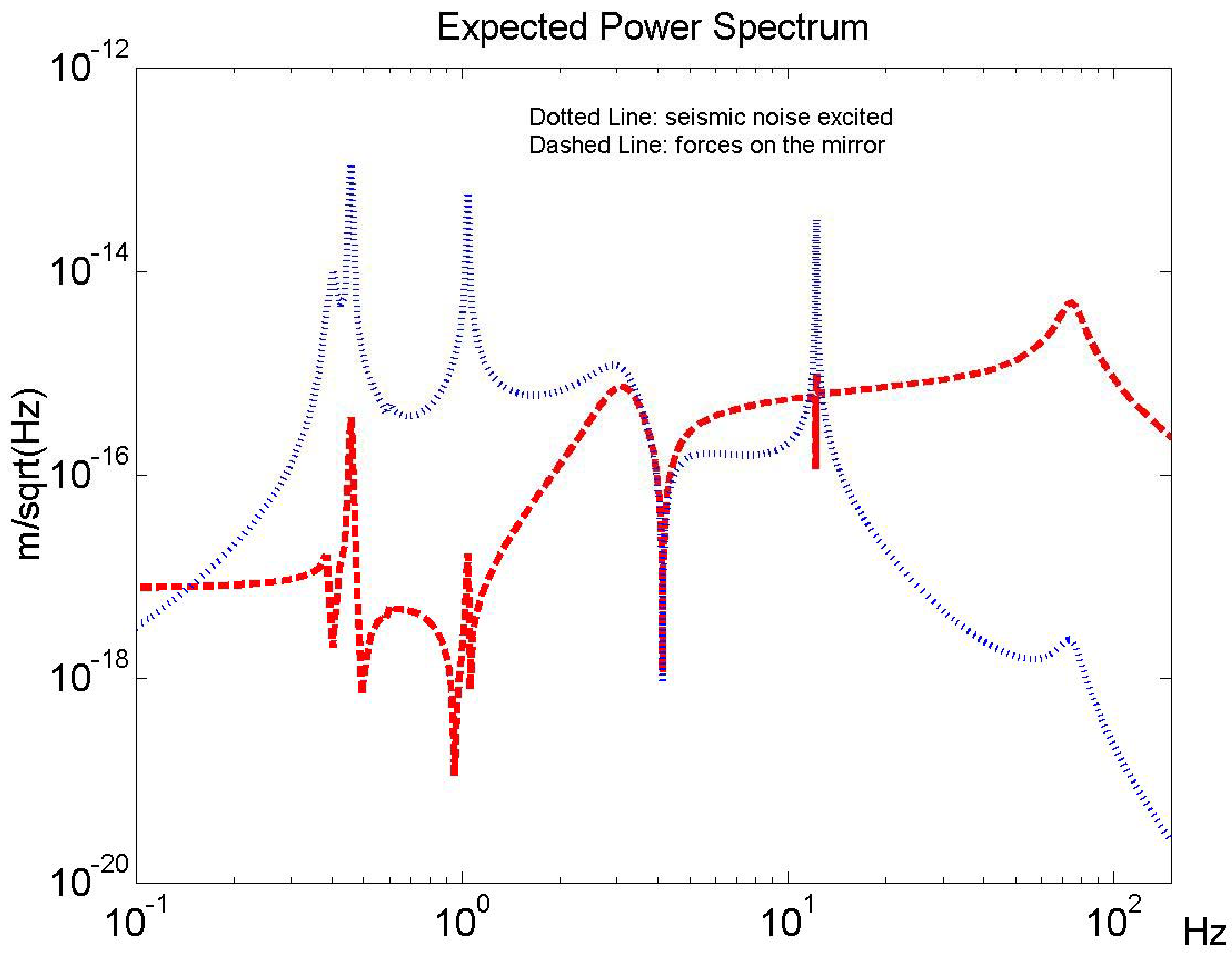


Thermal noise Extimation
m/sqrt(Hz)
Hz
dotted line: open loop without optical spring
dashed line: open loop with optical spring
continuus line: closed loop with optical spring


Error Signal Power Spectrum may400 7
m/sqrt(Hz)
Hz
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-1}
10^{0}
10^{1}
10^{2}

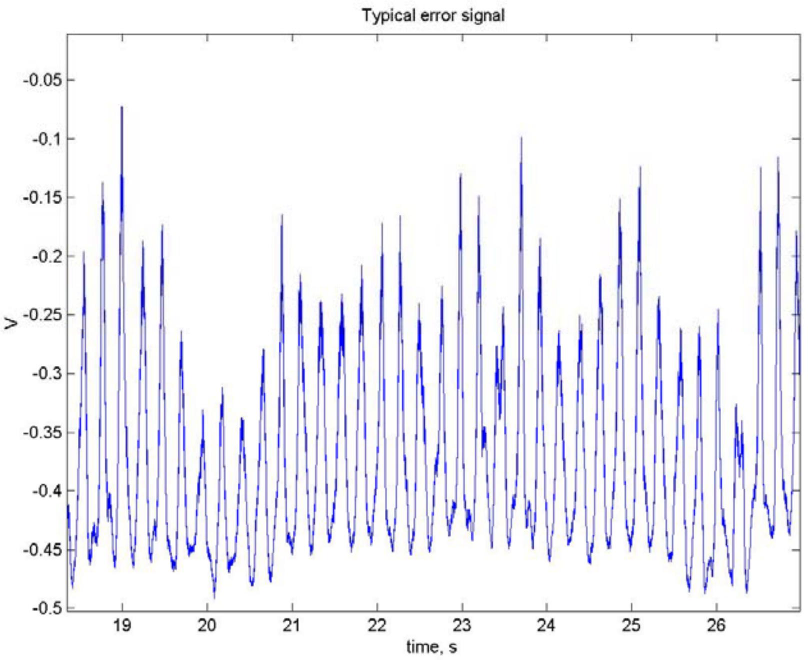


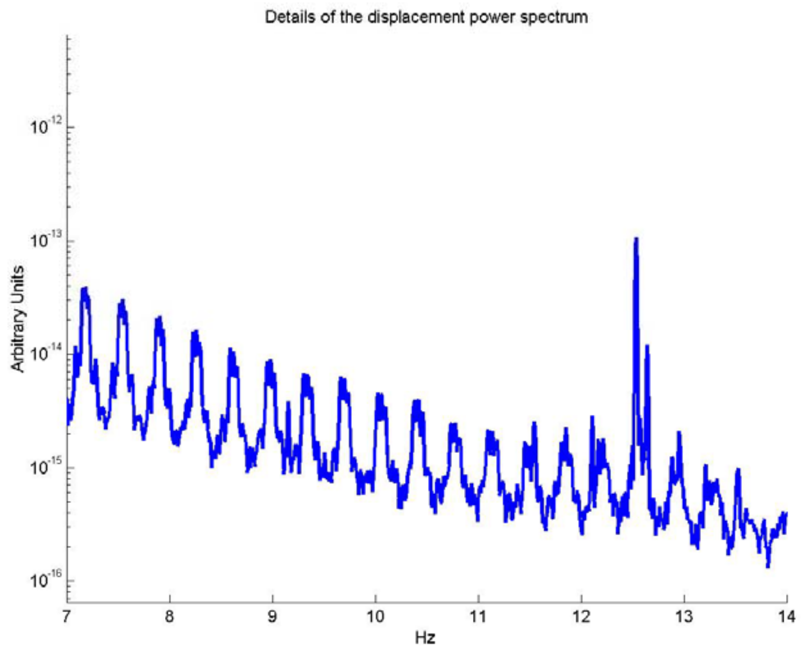
Measurements and model
x 10^-5
3.5
3
2.5
2
1.5
1
0.5
A.U.
50
60
70
80
90
100
110
120
Hz

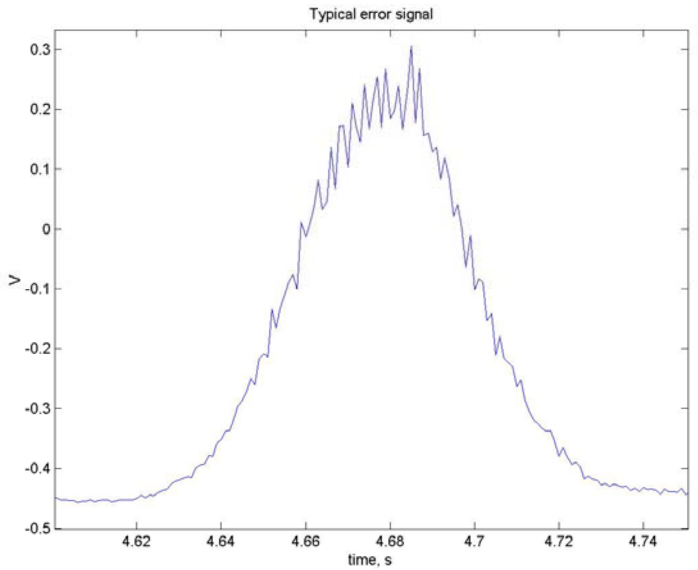


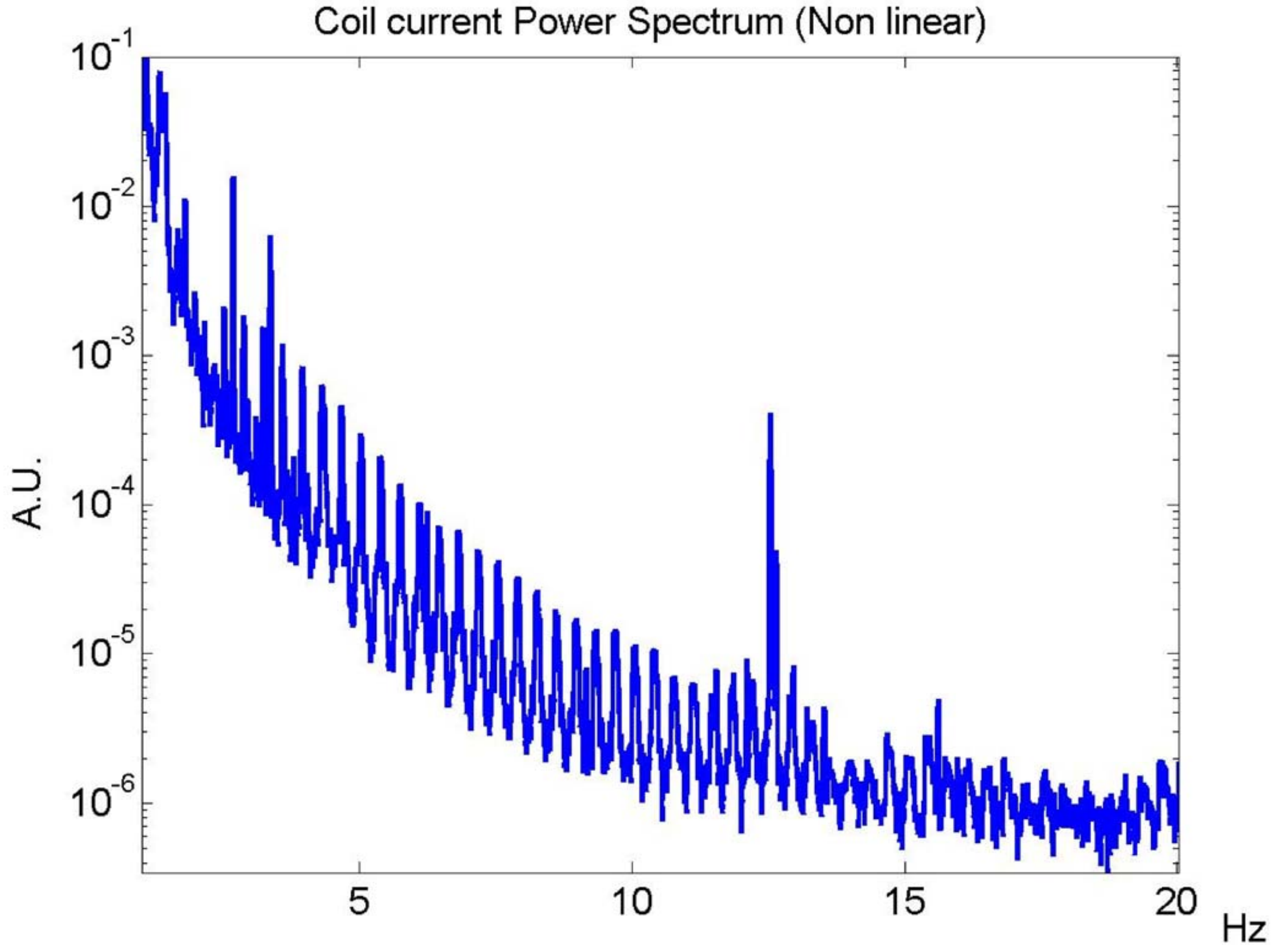
Expected Power Spectrum
Dotted Line: seismic noise excited
Dashed Line: forces on the mirror
m/sqrt(Hz)
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-1}
10^{0}
10^{1}
10^{2}
Hz

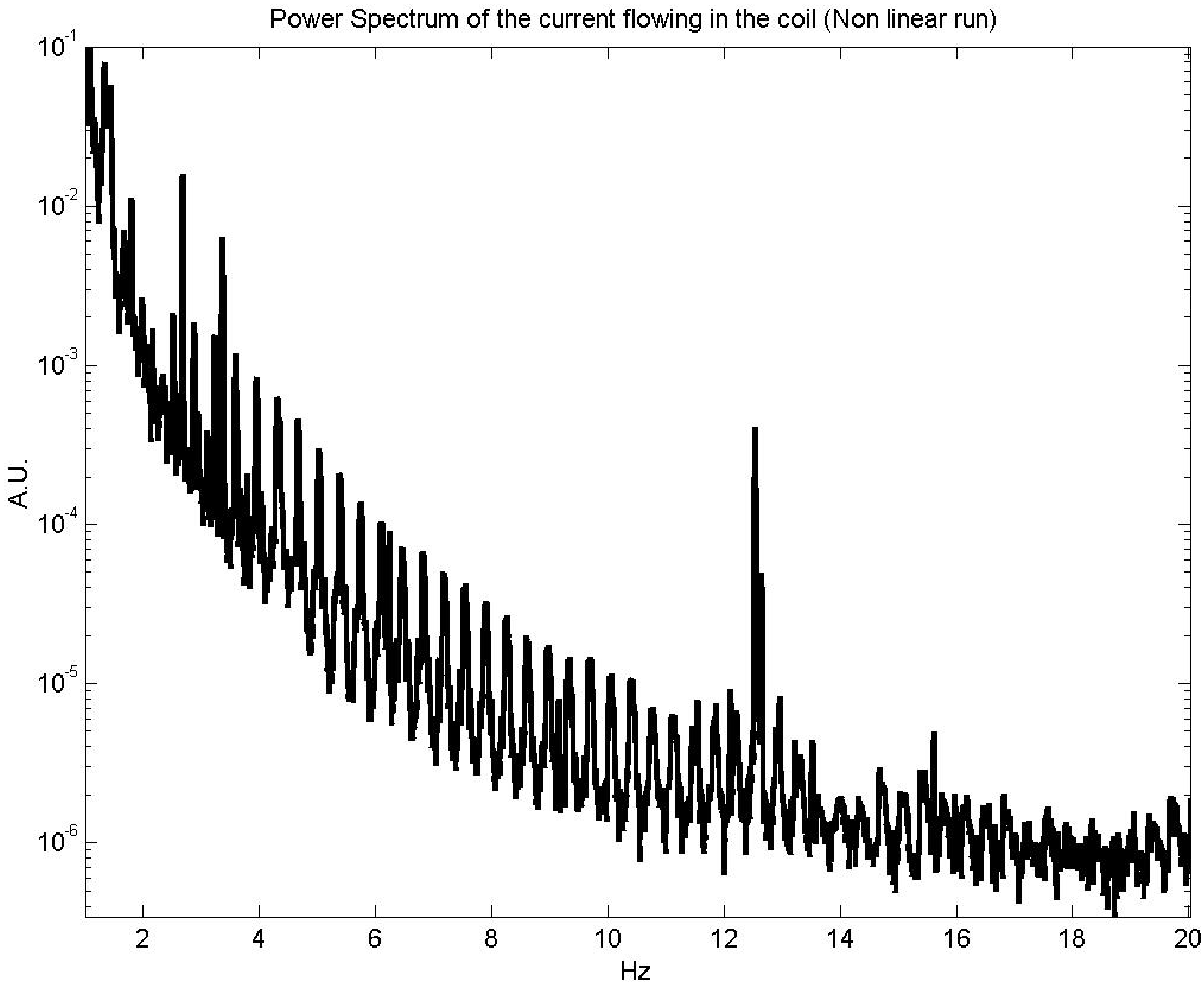
An-harmonic runs


Typical error signal
V
time, s


Details of the displacement power spectrum
Arbitrary Units
Hz


Typical error signal
V
time, s

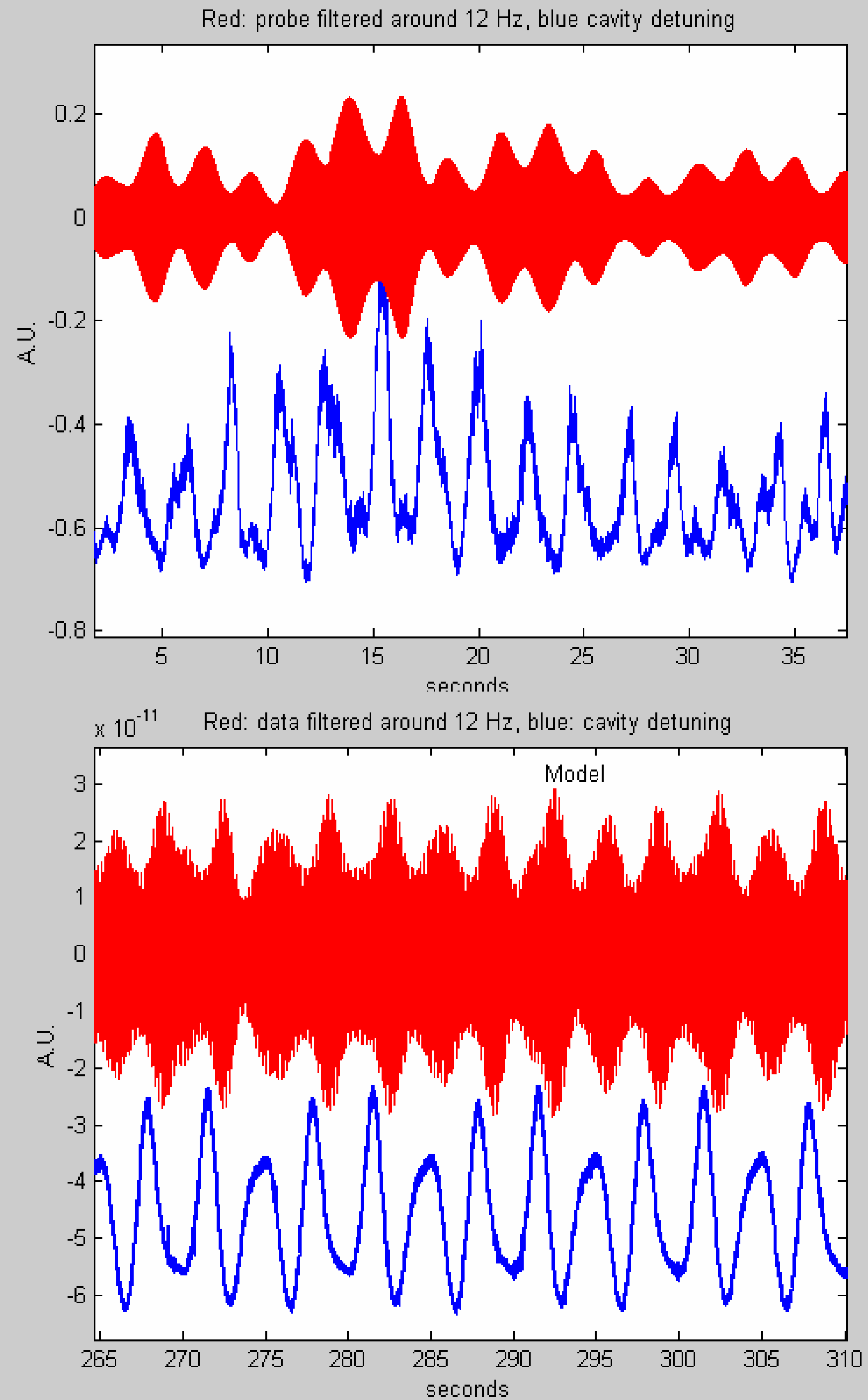

Coil current Power Spectrum (Non linear)
A.U.
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
5
10
15
20
Hz

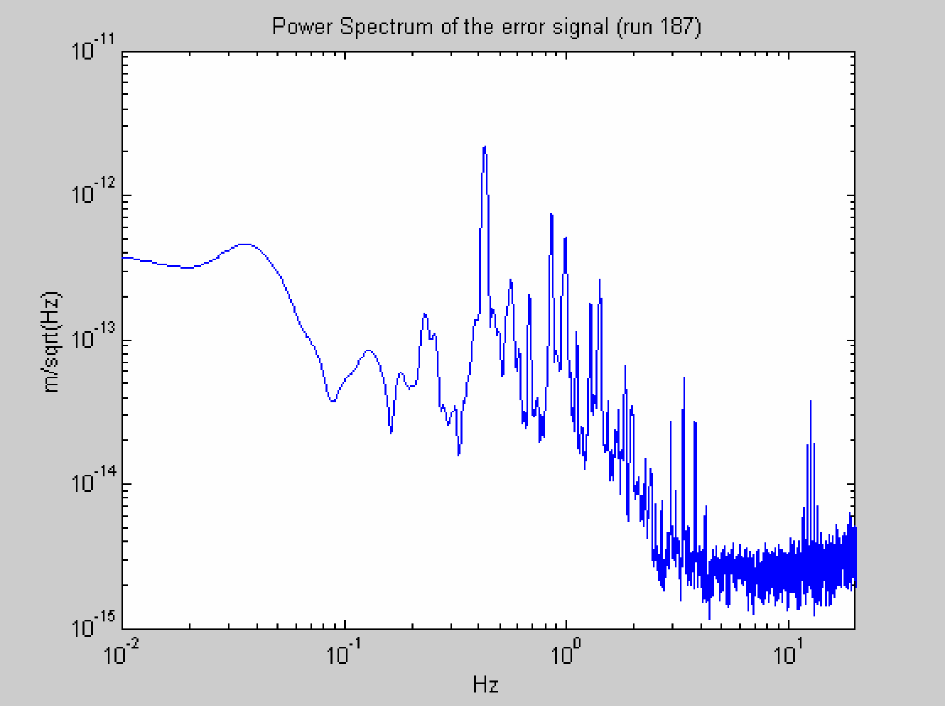


Power Spectrum of the current flowing in the coil (Non linear run)
A.U.
Hz
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
2
4
6
8
10
12
14
16
18
20

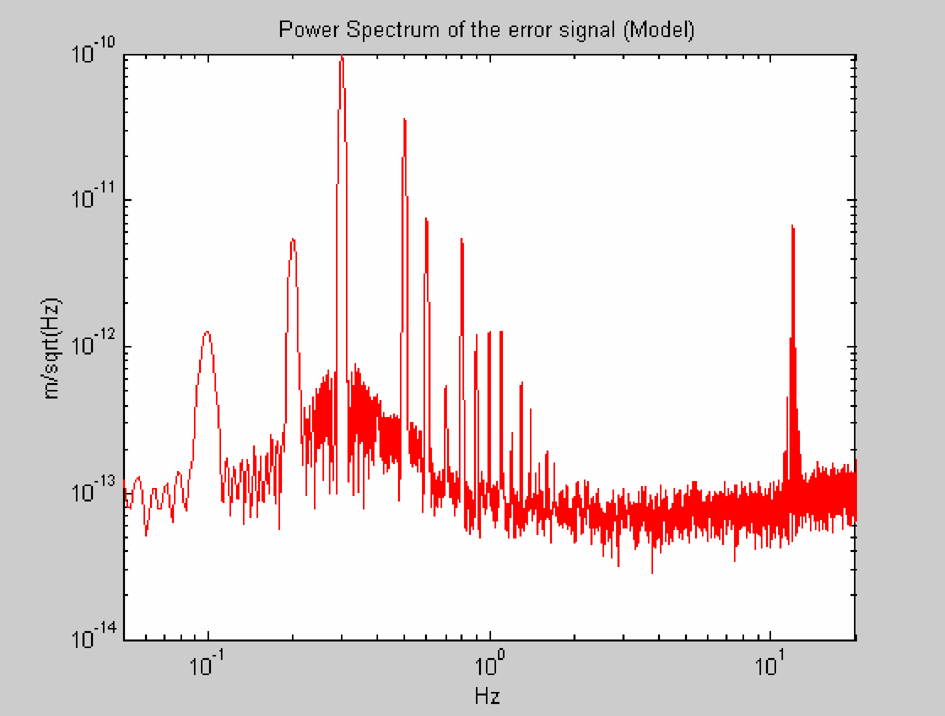
The model (non linear case)

- The model consists on a set of differential equations (2), which takes into account two pendulums, and the optical spring as a standard linear one plus the second order term; the masses are considered point-like, and the wires mass-less, the feedback is the LFF one. In this case the solution is numerical, and standard initial conditions of the experiment are used

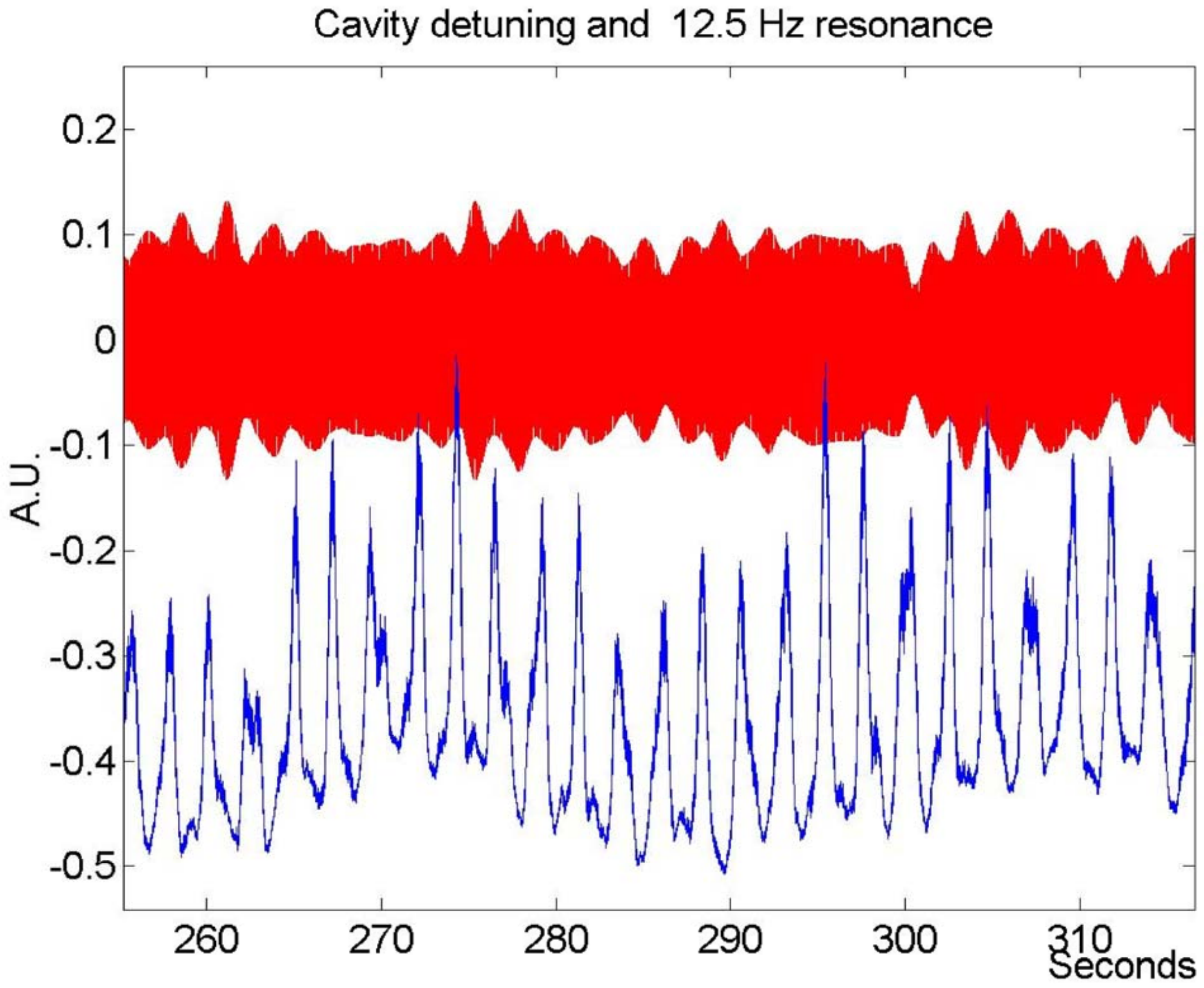

Red: probe filtered around 12 Hz, blue cavity detuning
A.U.
0.2
0
-0.2
-0.4
-0.6
-0.8
5
10
15
20
25
30
35
seconds
Red: data filtered around 12 Hz, blue: cavity detuning
x 10^-11
Model
A.U.
3
2
1
0
-1
-2
-3
-4
-5
-6
265
270
275
280
285
290
295
300
305
310
seconds



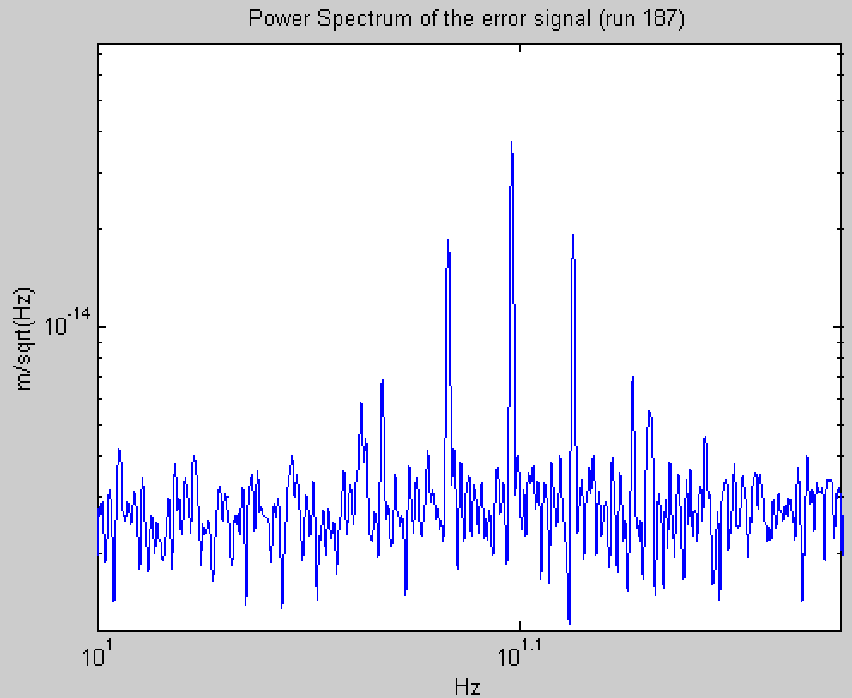
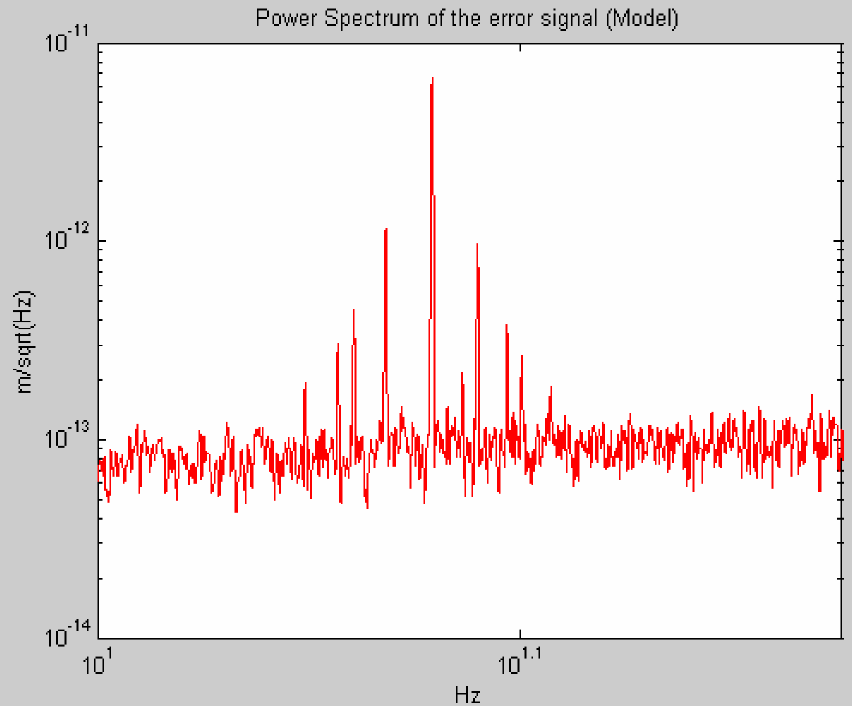
Power Spectrum of the error signal (run 187)
m/sqrt(Hz)
Hz



Power Spectrum of the error signal (Model)
m/sqrt(Hz)
Hz

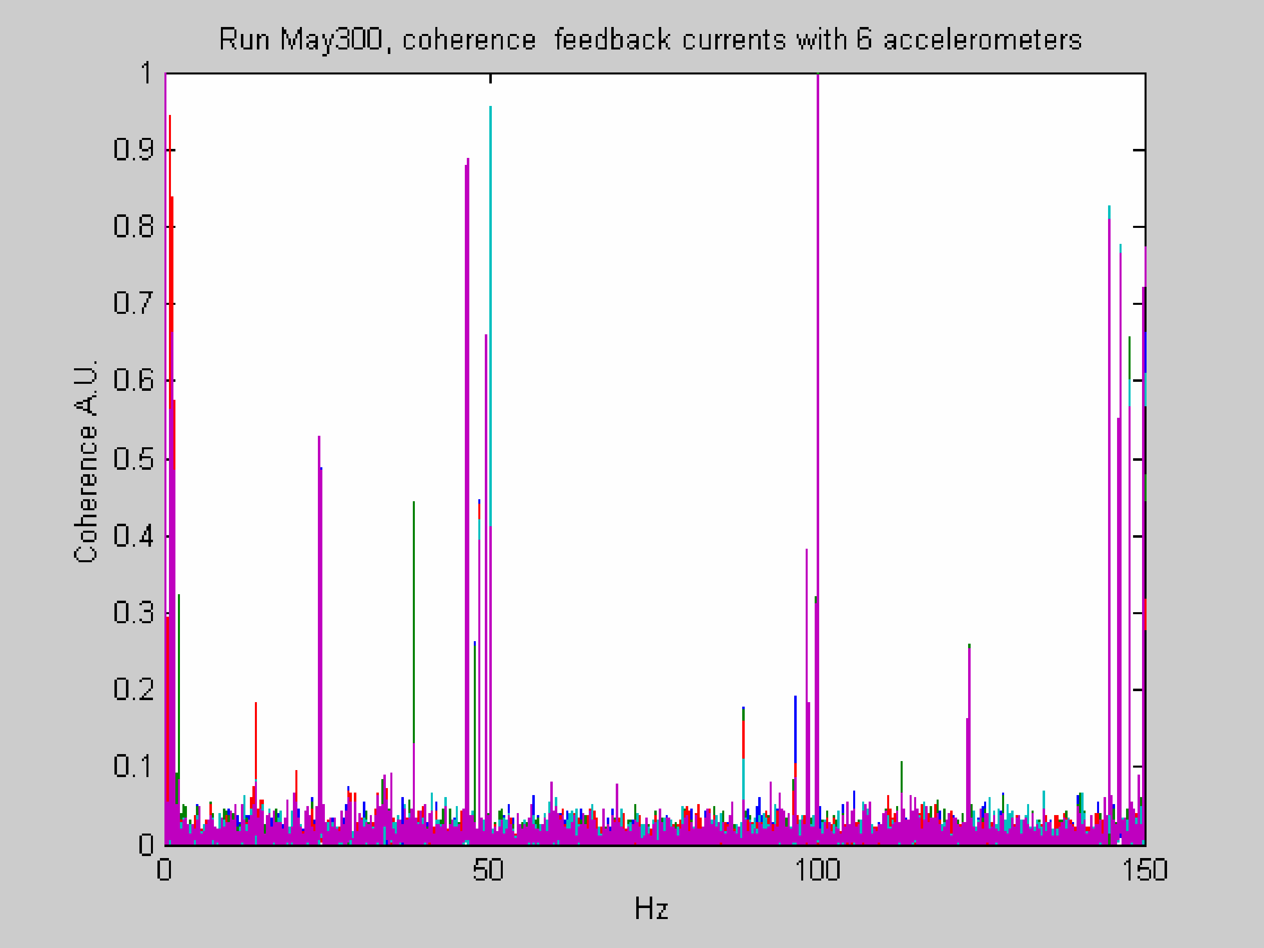


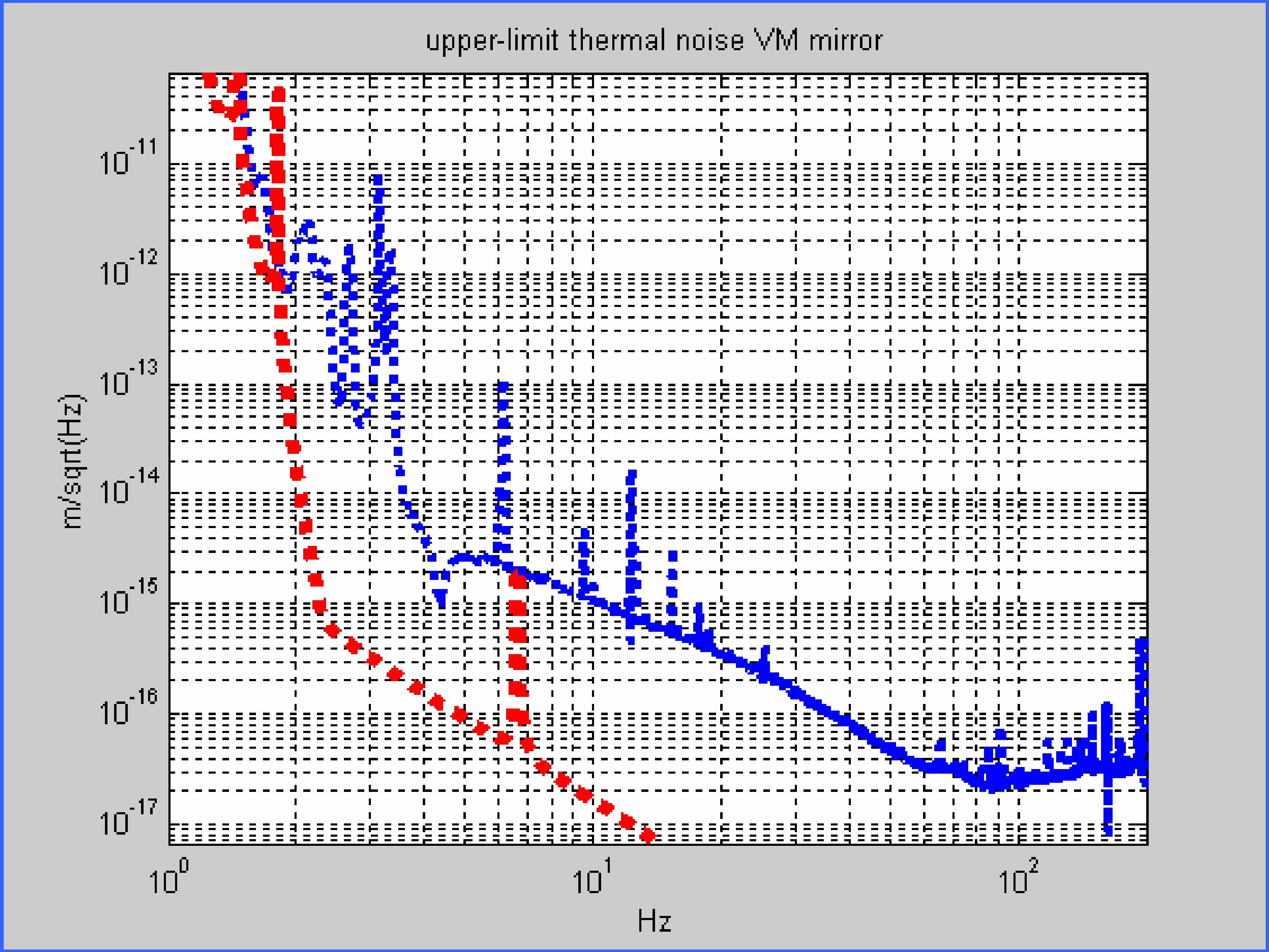
Cavity detuning and 12.5 Hz resonance
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
A.U.
260
270
280
290
300
310
Seconds


Power Spectrum of the error signal (run 187)
m/sqrt(Hz)
10^-14
10^1
10^1.1
Hz

Power Spectrum of the error signal (Model)
m/sqrt(Hz)
10^-11
10^-12
10^-13
10^-14
10^1
10^1.1
Hz

About the SA suspension….

Seismic noise is ruled out

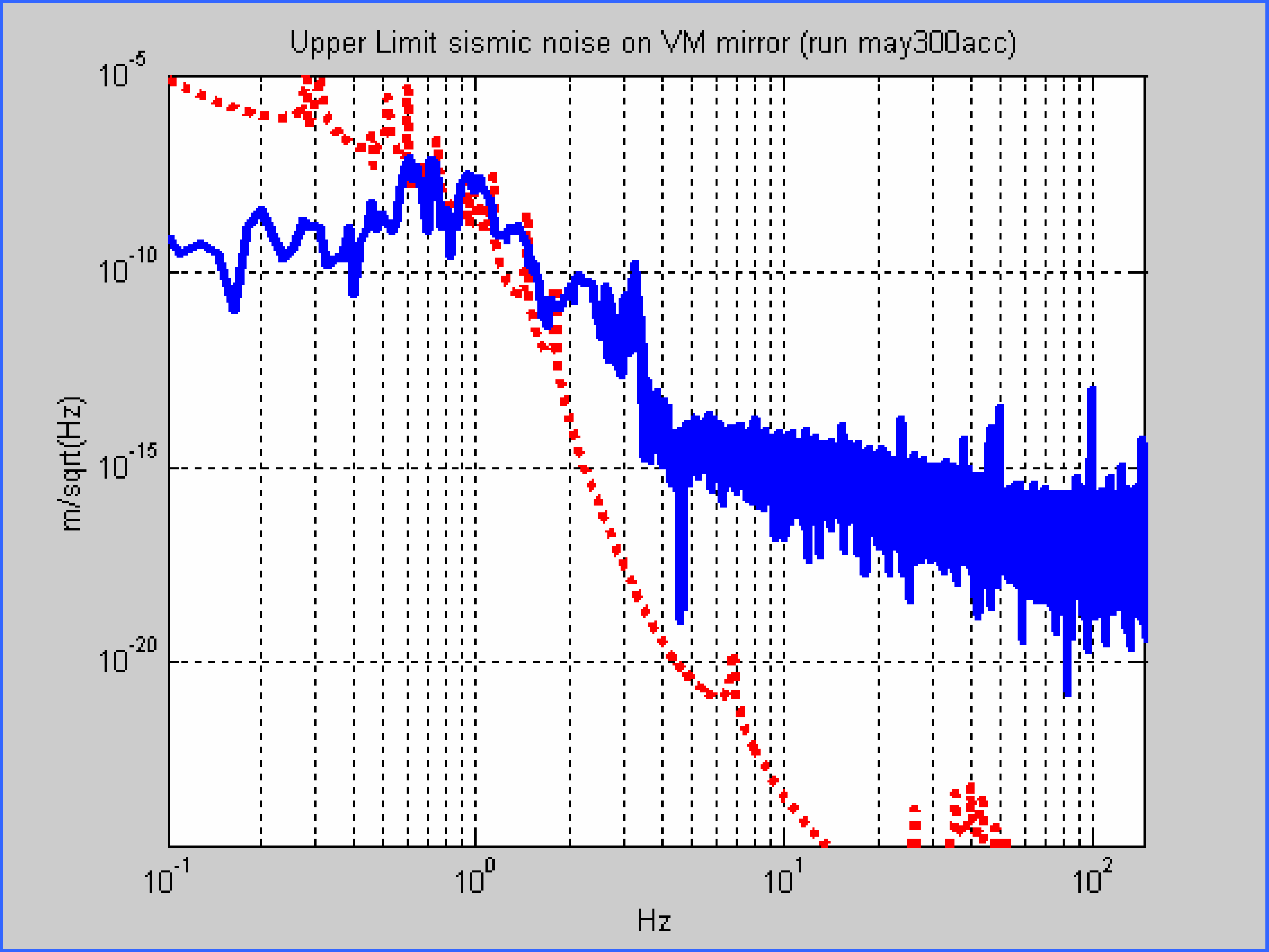




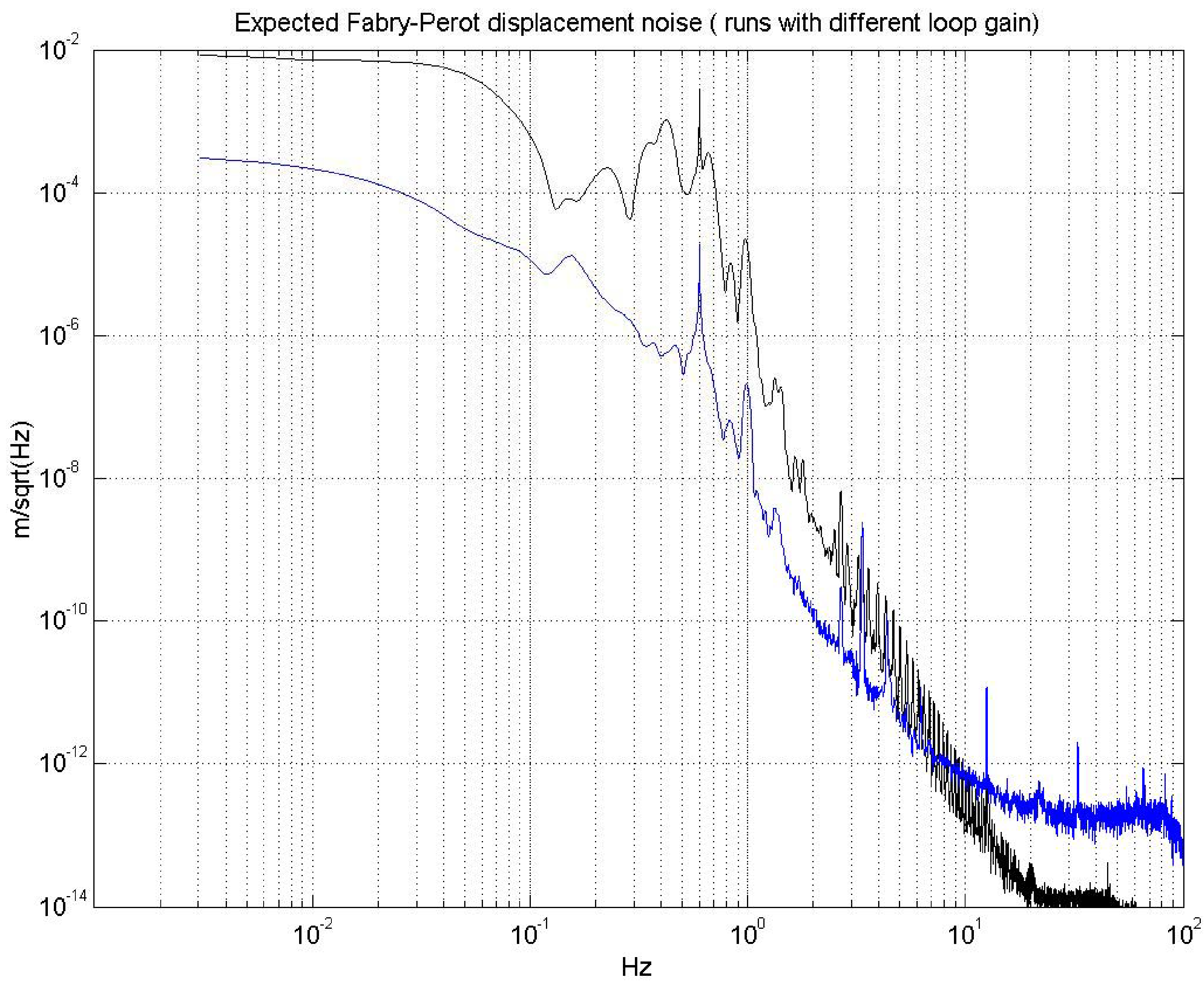
upper-limit thermal noise VM mirror
m/sqrt(Hz)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{0}
10^{1}
10^{2}
Hz

Conclusions

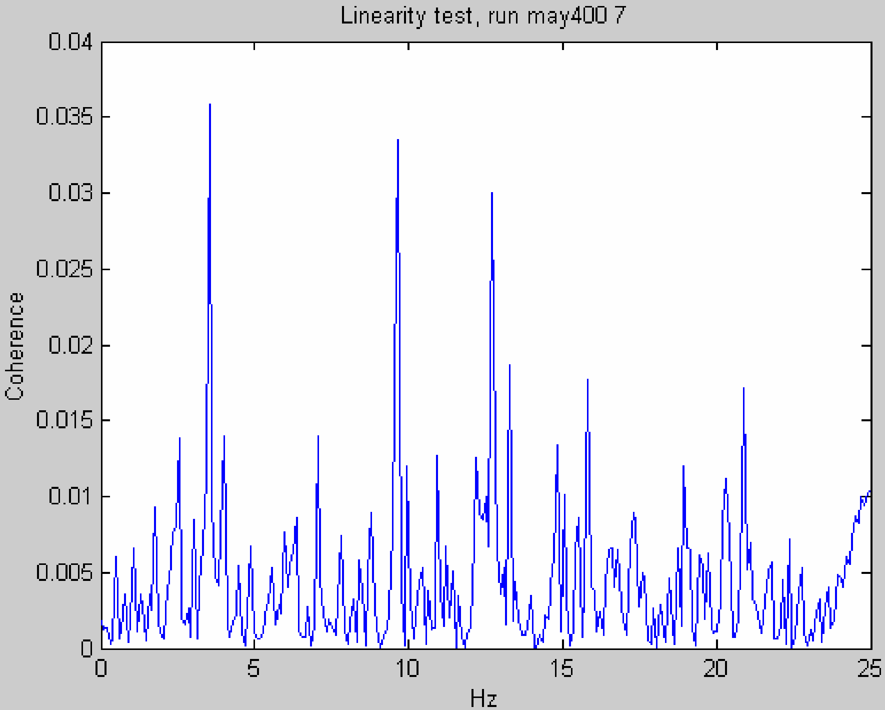
- Simple models, which take into account the presence of a strong optical spring acting against the two mirrors of the Fabry-Perot cavity well explain the data, in the linear and non linear case.
- The spring is compatible with the theoretical one and the LFF parameters (first and second order term)

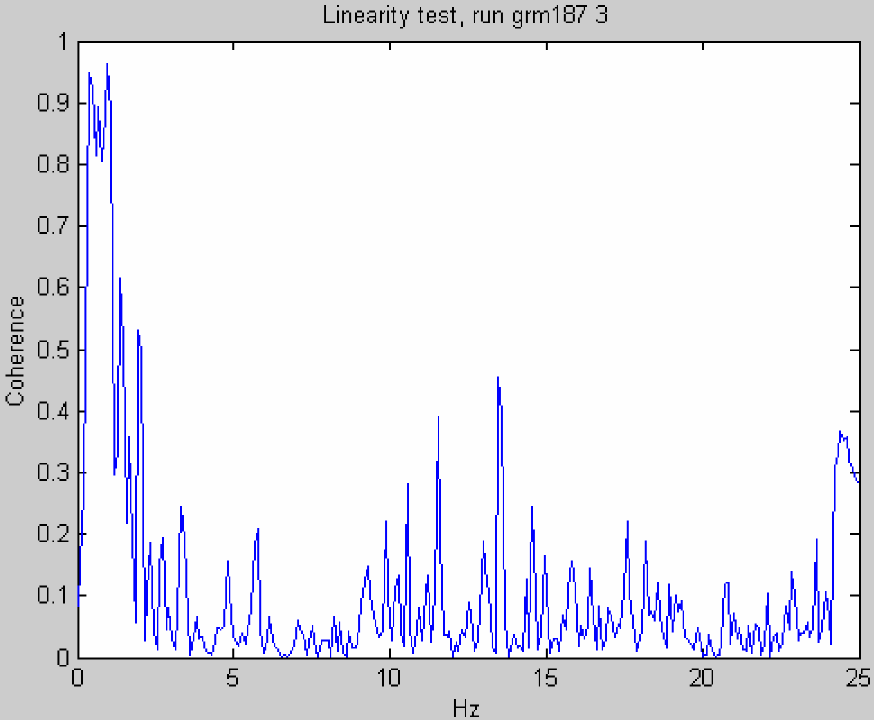


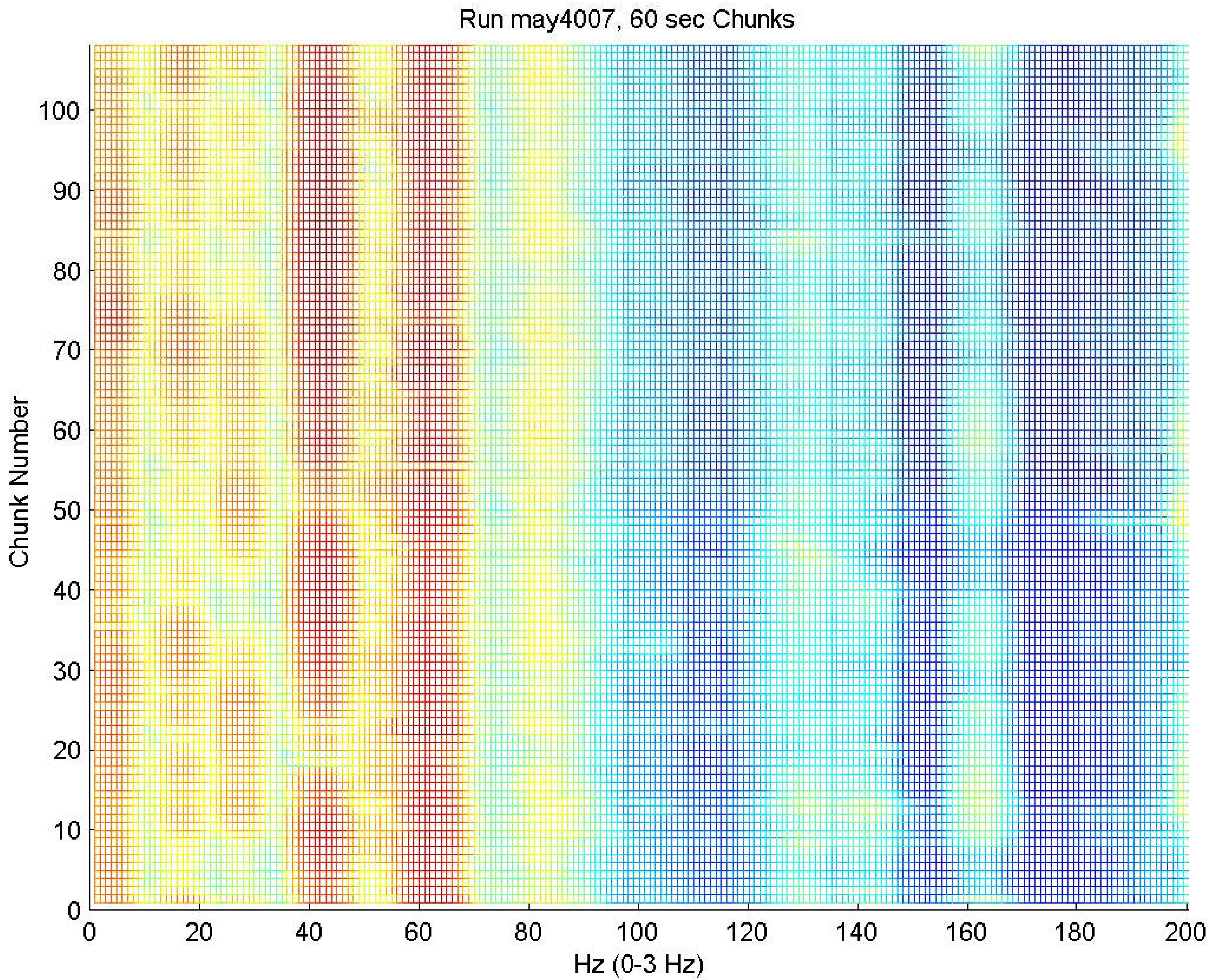
Upper Limit sismic noise on VM mirror (run may300acc)
m/sqrt(Hz)
Hz
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-1}
10^{0}
10^{1}
10^{2}



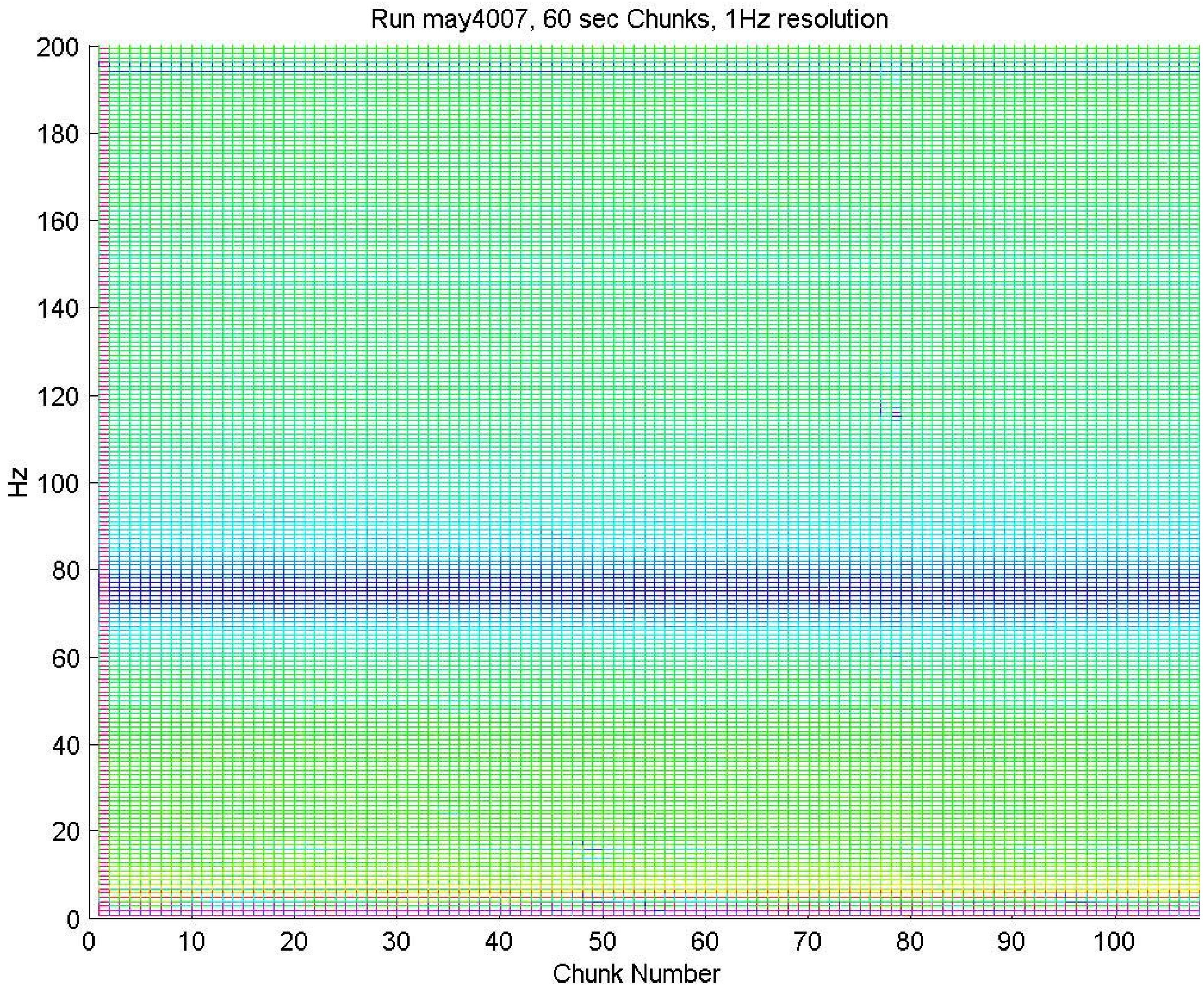
Expected Fabry-Perot displacement noise (runs with different loop gain)
m/sqrt(Hz)
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Hz


Linearity test, run may400 7
Coherence
Hz
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0
5
10
15
20
25


Linearity test, run grm187 3
Coherence
Hz
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25



Run may4007, 60 sec Chunks
Chunk Number
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120
140
160
180
200
Hz (0-3 Hz)


Run may4007, 60 sec Chunks, 1Hz resolution
Hz
200
180
160
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
80
90
100
Chunk Number