Seismic Isolation of GW detectors

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Introduction
Virgo and LIGO sensitivity

Imagine to drop a glass of wine (or water) in the ocean…….

Ocean Surface (S):
70% x 4π x R_terra^2 =
0.7 x 4 x 3.14 x (6.37e6 m)^2
~ 3.6e14 m^2

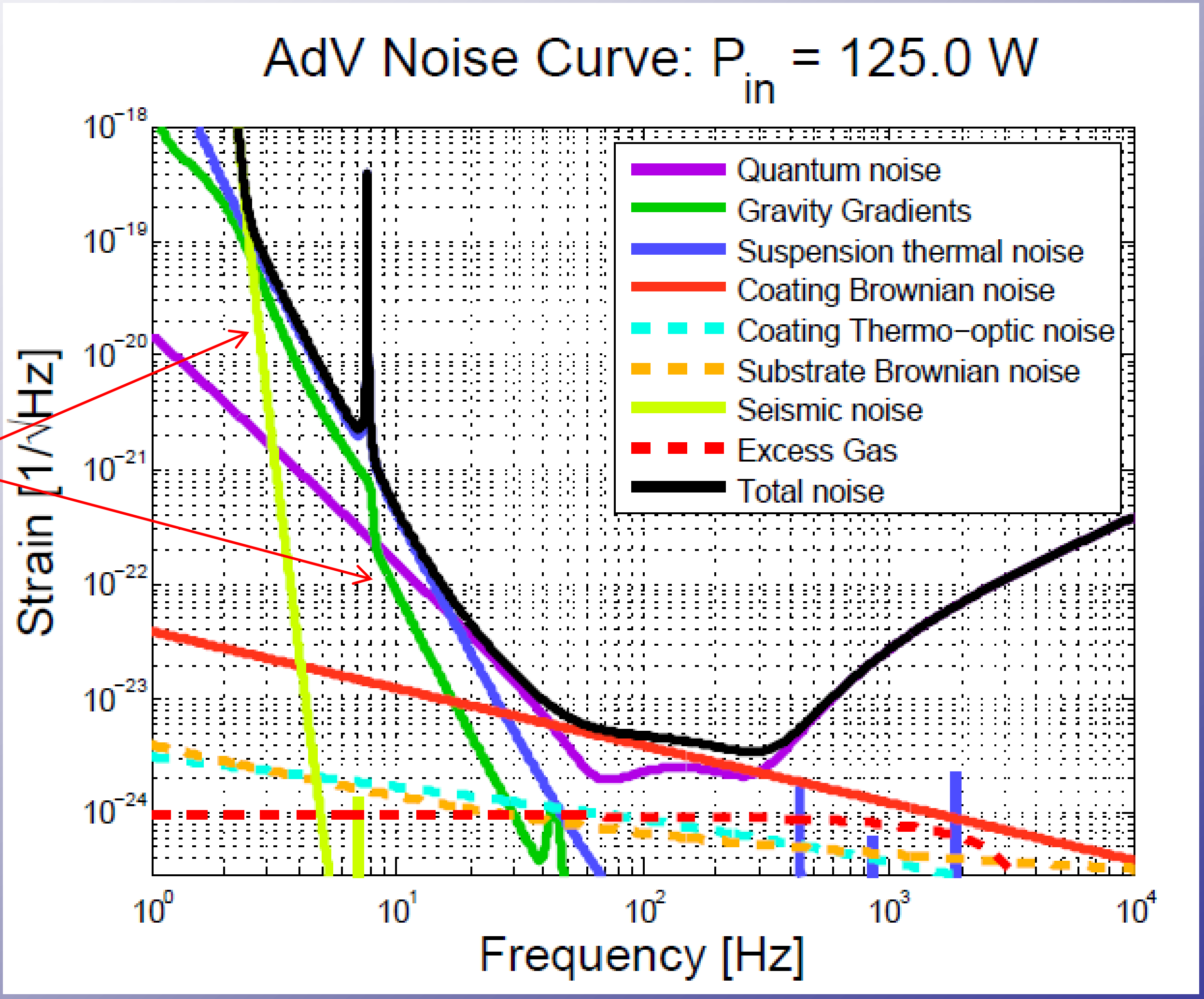
Volume of the glass (V):
~ 0.25e-3 m^3

Increase of the global sea level:
h ~ V / S ~ 1e-18 m

This is the level of sensitivity we need to reach with GW detectors !!

Introduction
AdVirgo Noise Budget

Newtonian and Seismic noise dominate at low frequency



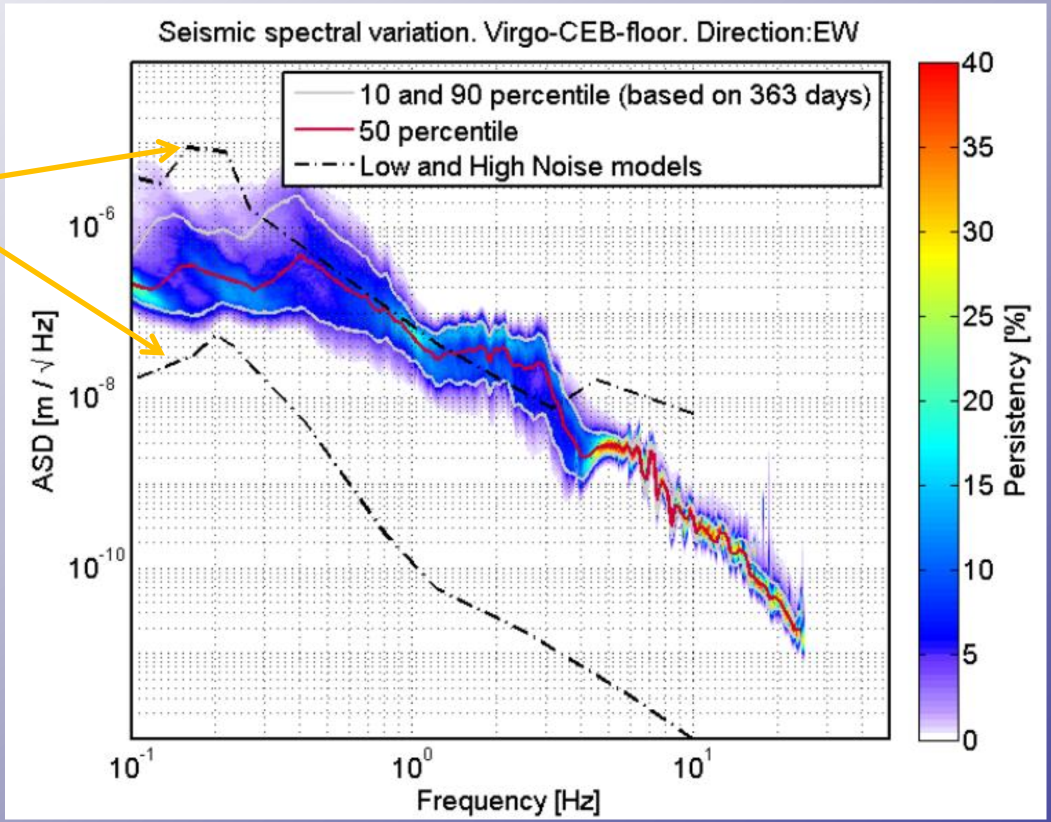
Introduction

Seismic Noise on Earth

- Seismic noise has both natural and human origins and can vary by few orders of magnitude from site to site.
- Al ground motion displacement spectra observed worldwide share some common characteristics: they have essentially the same amplitude in all three orthogonal space directions and they exhibit a low pass behavior that follows the empirical law for f > 0.1 Hz

$$x(f) \sim A\,(1\ \mathrm{Hz/f})^2 \text{ m/sqrt(Hz)}$$

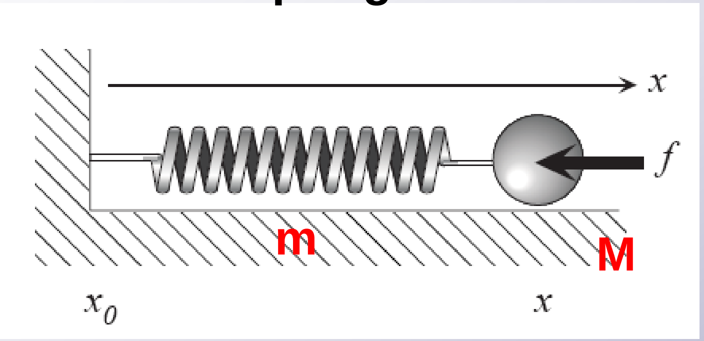
Peterson's High and Low Noise Models



Introduction
Harmonic Oscillators as Mechanical filters

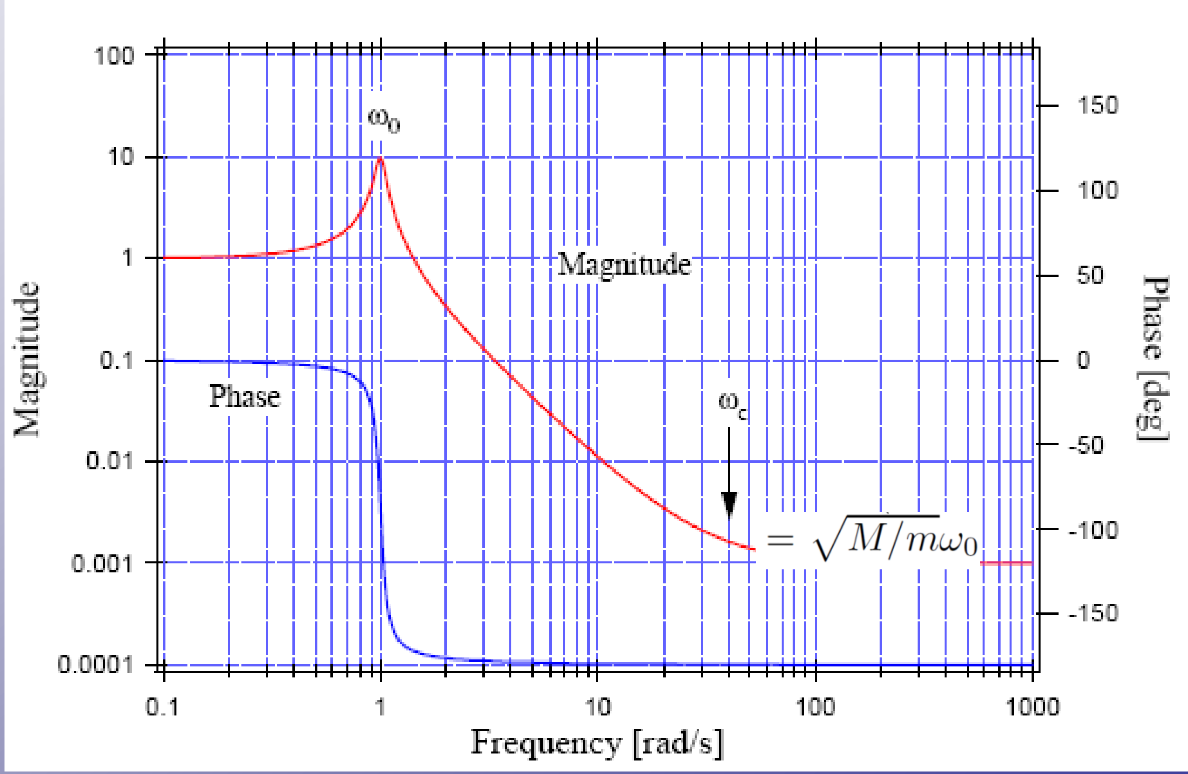
At frequencies higher than the oscillator resonance, the transfer function of an harmonic oscillator is equivalent to a second-order low pass filter.

Massive Spring

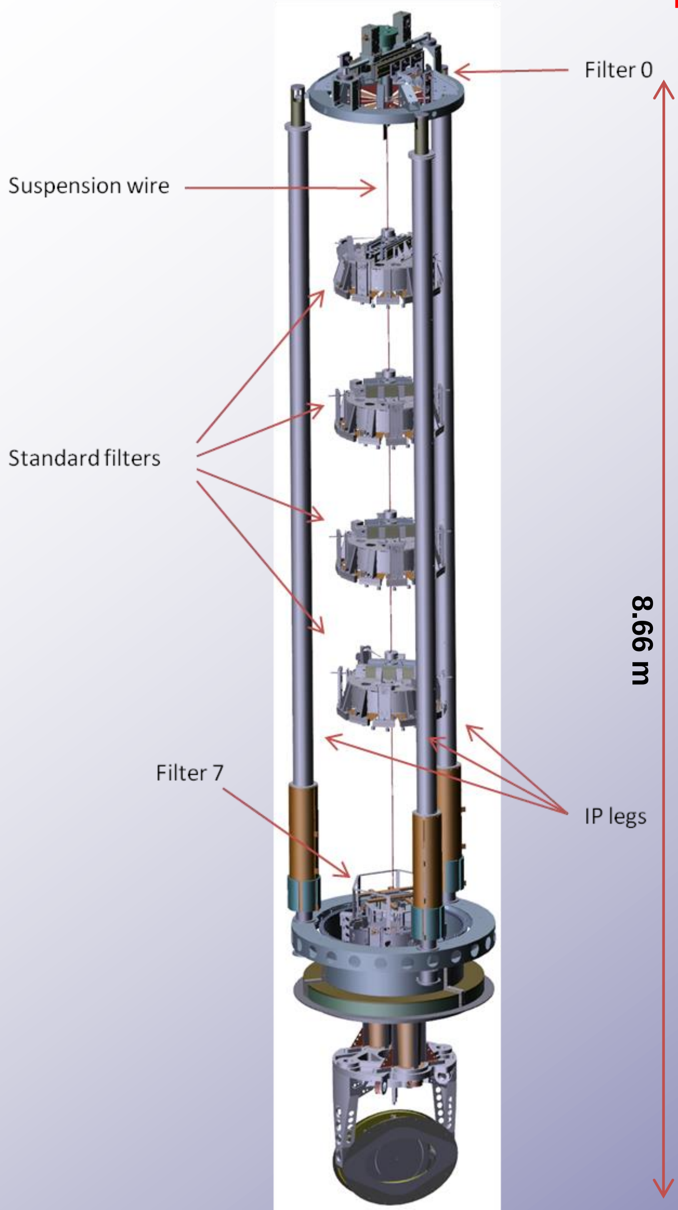


$$H_X = \frac{\omega_0^2(1+i\phi) + \frac{m}{M}\omega^2}{\omega_0^2(1+i\phi) - \omega^2 + i\frac{\gamma}{M}\omega}$$

Transfer Function

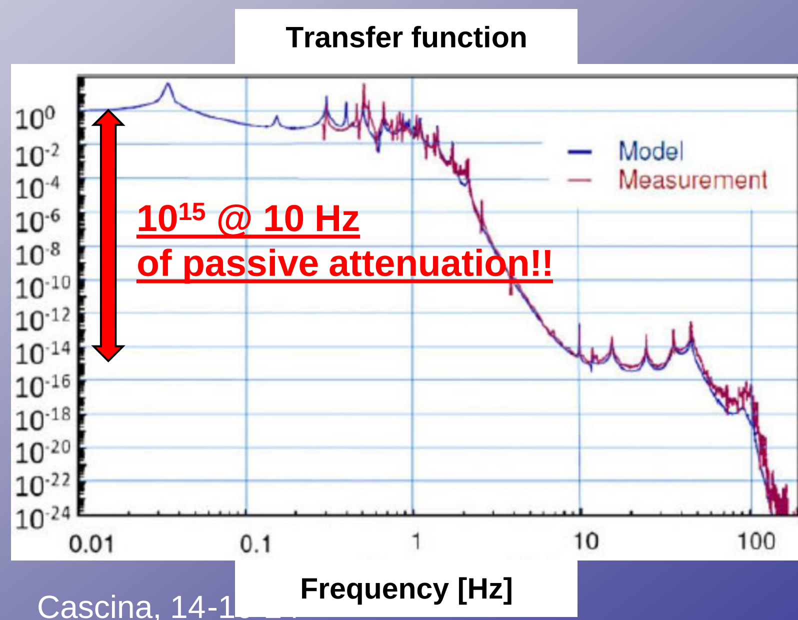


AdVirgo Superattenuator
The superattenuator (SA)



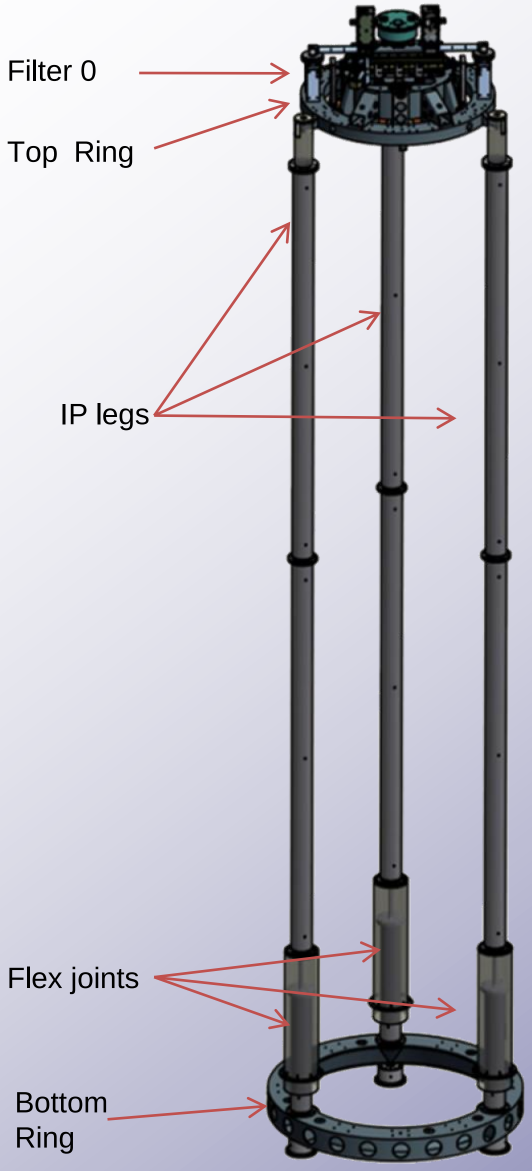
The AdVirgo superattenuator (SA) is a complex mechanical device capable of providing more than 10 orders of magnitude of passive seismic isolation in all six degrees of freedom above a few Hz

- The SA is a passive mechanical system constituted by a 5 stage pendulum supported by a 3-leg elastic pre-isolator called inverted pendulum (IP).
- All the normal mode resonance frequencies of the SA are kept below 2 Hz.
- The SA mechanical structure, consists of three fundamental parts: the inverted pendulum, the chain of standard filters, the payload.
- Mechanical design for AdVirgo is essentially the same of Virgo except for the payload.

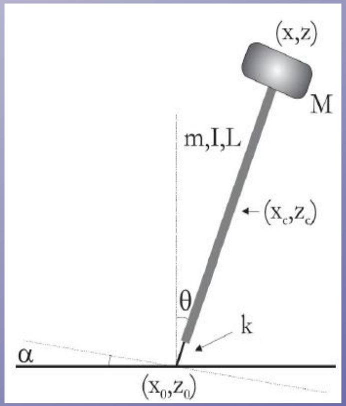


AdVirgo Superattenuator

The inverted pendulum



- A low frequency pre-isolator constituted of three 6 m-long hollow legs, each one connected to the ground through a flexible joint and supporting an interconnecting structure (the top ring) on its top.
- The structure horizontal normal modes are tuned at about 30-40 mHz.
- A simple mechanical model such as this



Gravitational Anti-spring

gives

$$\omega_0 = \frac{k - (M + m/2)g/L}{M + m/4 + I/L^2}$$

- Since the system is very soft, it requires very low forces to be moved:

for f<<f0 $F \simeq M\omega_0{}^2 x$

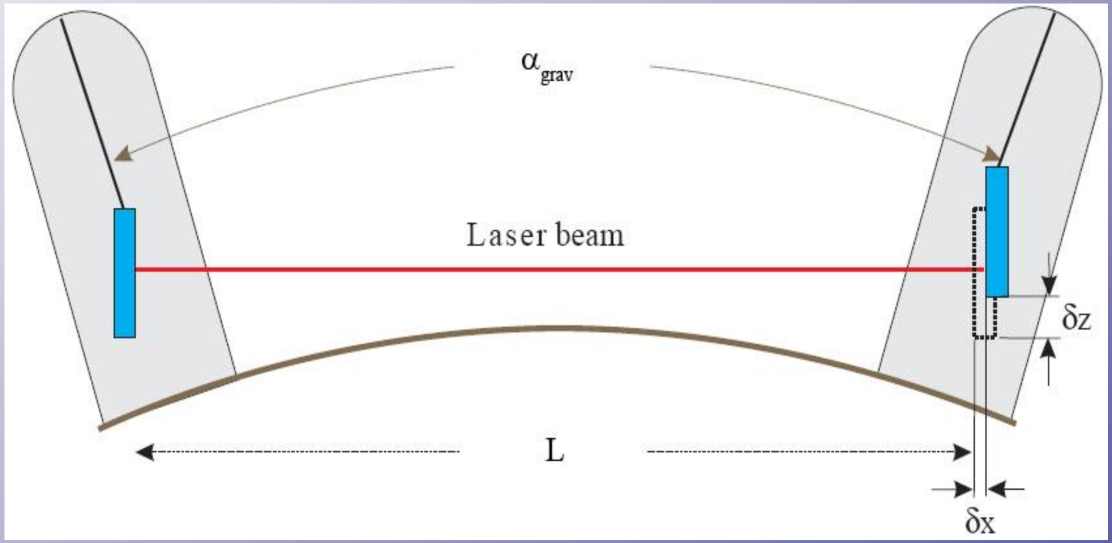
- The top ring is a mechanical support for an additional seismic filter, called filter 0, similar to those used in the chain.
- The filter 0 is equipped with a set of sensors and actuators, placed in a pinwheel configuration, that are used to actively damp the IP resonance modes.

AdVirgo Superattenuator

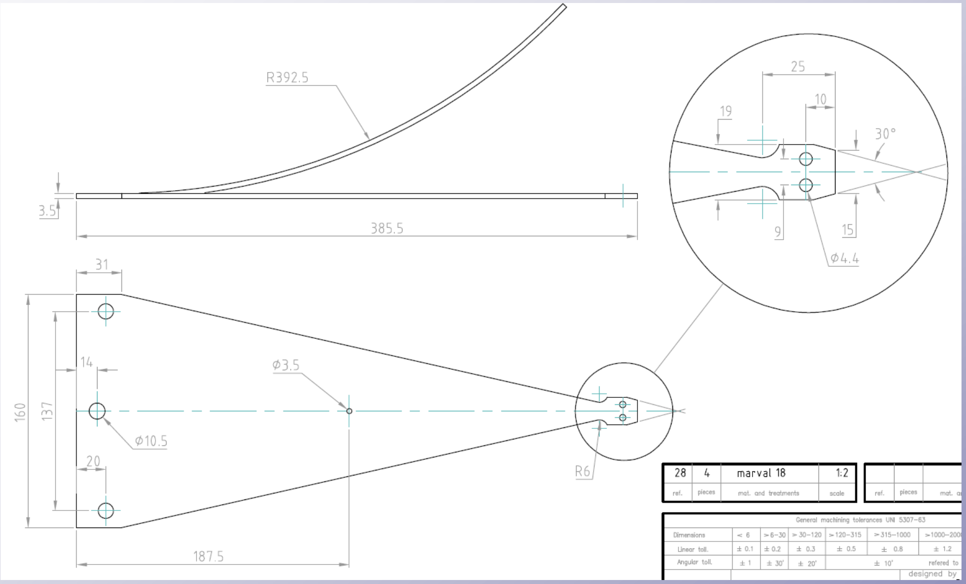
Why vertical attenuation ?

- The input and output mirrors of a Fabry-Perot cavity form an angle alpha_grav = L/r = $5*10^{-4}$ rad (where L = 3 km is the cavity length and r is the Earth radius) with the global vertical direction. Therefore vertical displacement Δz has effect along the beam direction, producing a variation alpha_grav*Δz of the optical path.

- The suspension system causes even larger mechanical couplings (1%), due to structural reasons.



AdVirgo Superattenuator
Vertical attenuation: Blades

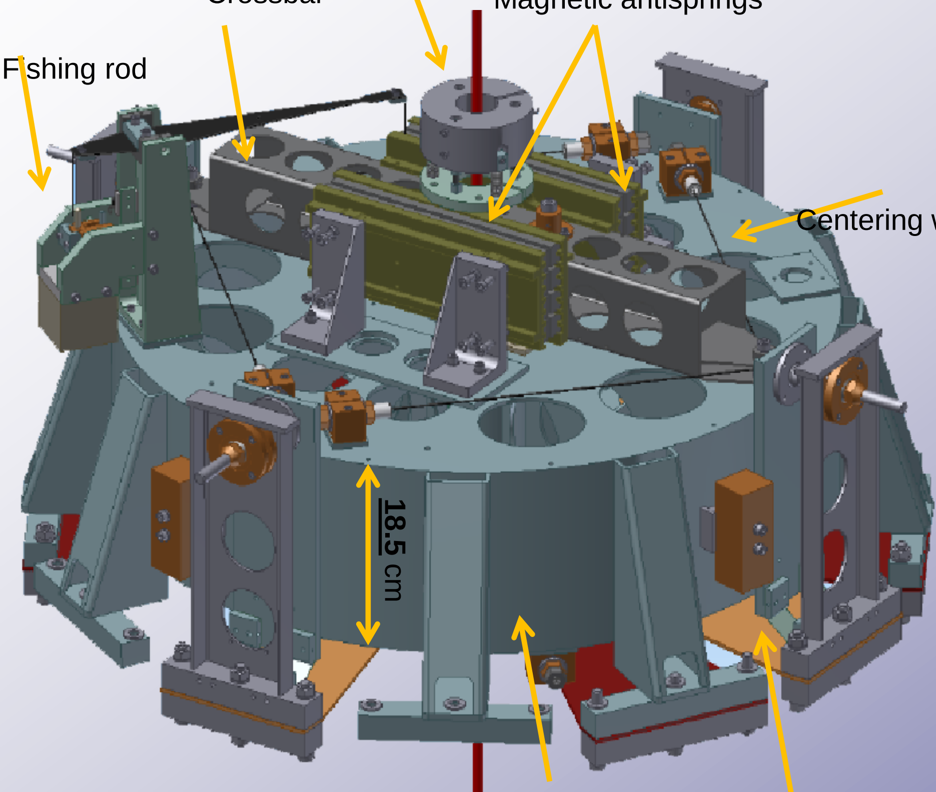


- All the maraging steel blades have a thickness of 3.5 mm, a length of 385.5 mm, while the width of the triangular base changes according with the load to be supported.
- The number of blades ranges from 12 (in the first filter of the chain) to 4 (in the filter 7) according to the suspended load. A total of 52 blades is needed for a long tower.
- The load M depends by the base width b, by the thickness t and length l with this law

$$M = \frac{Ebt^3}{12R_c gl}$$

AdVirgo Superattenuator

Vertical Attenuation: Standard filters

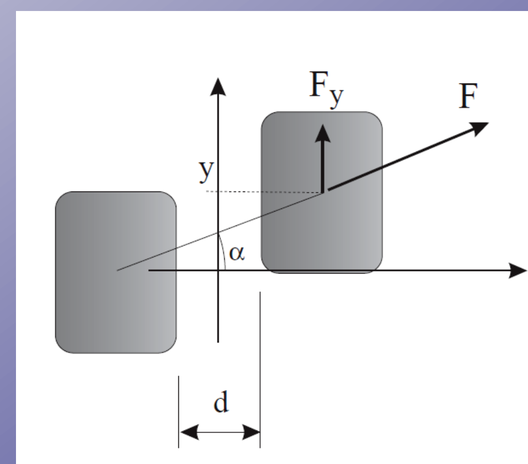


10^2 for f > 2 Hz
of passive attenuation
in both horizontal and vertical direction !!

The first four pendulum stages of the SA are denominated Standard Filters (SFs).

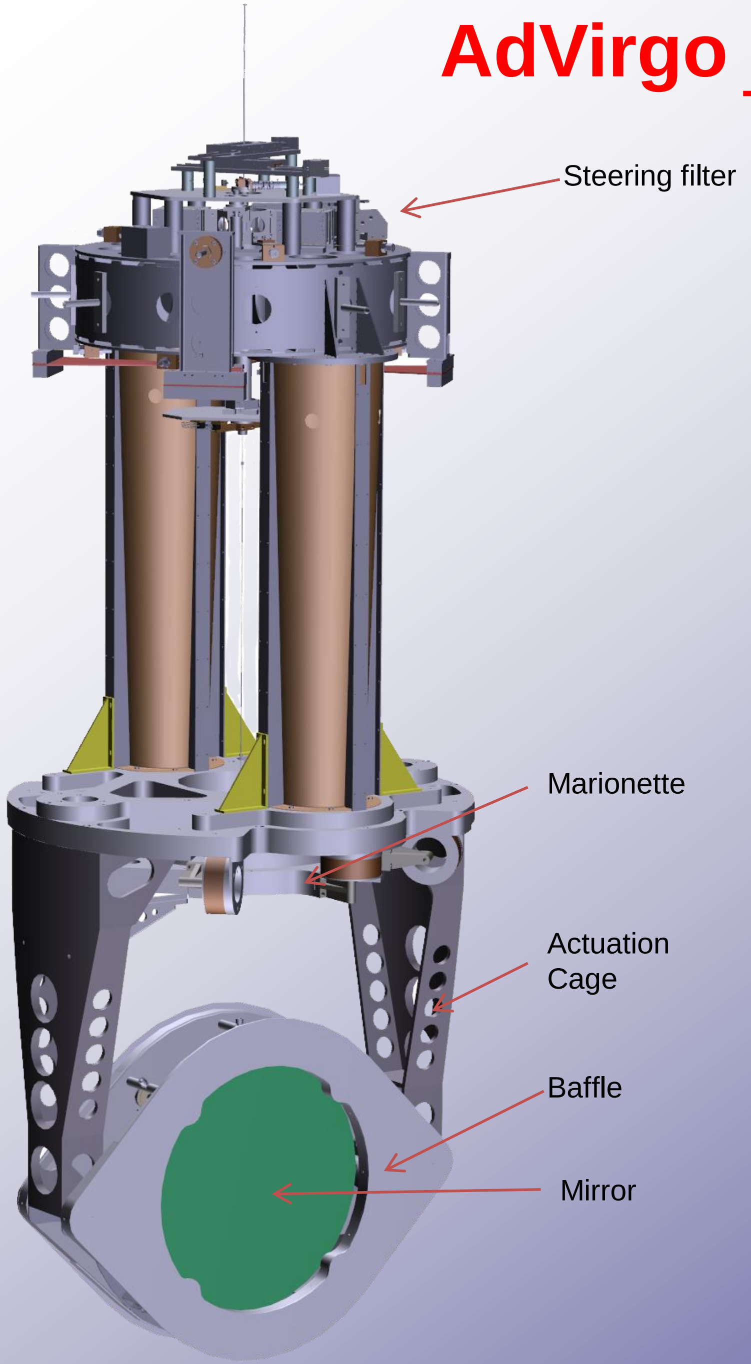
The SF is essentially a rigid steel cylinder supporting a set of maraging steel cantilevered triangular blades clamped along the outer surface of the filter body.

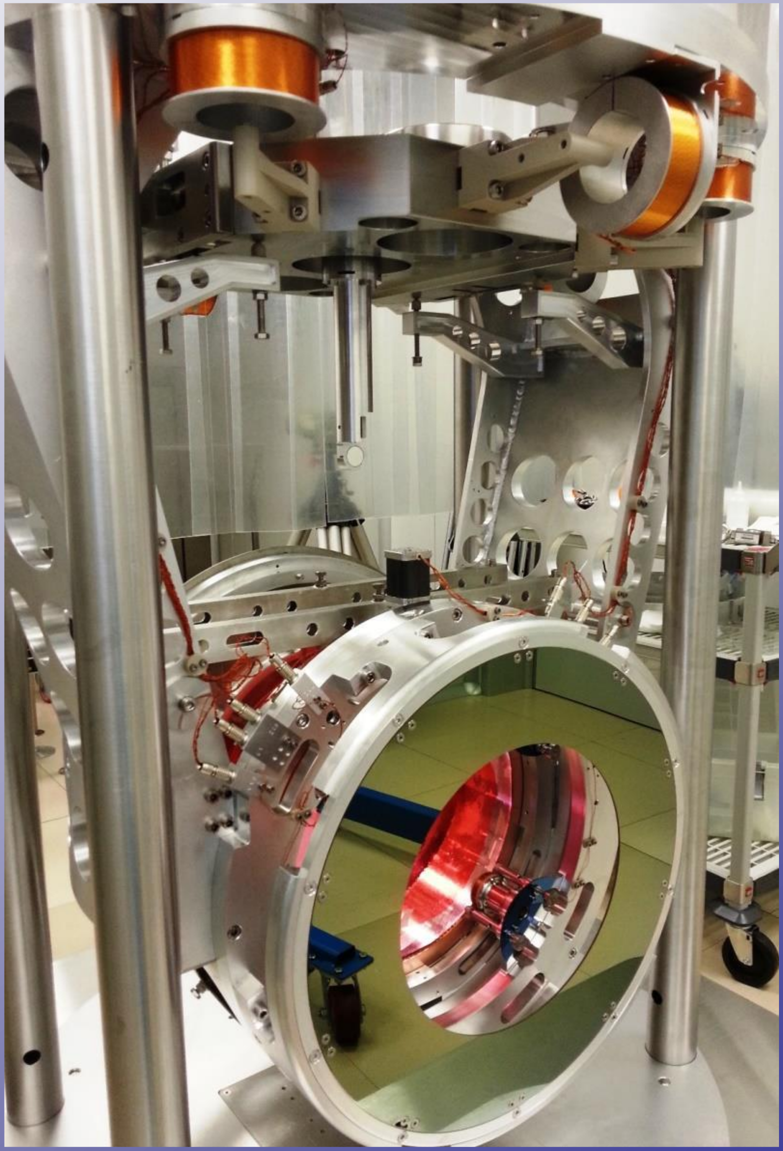
A magnetic anti-spring system, assembled on each filter, is designed to reduce its fundamental vertical frequency from about 1.5 Hz down below 0.5 Hz.



Magnetic antispring working principle

AdVirgo Superattenuator
The payload

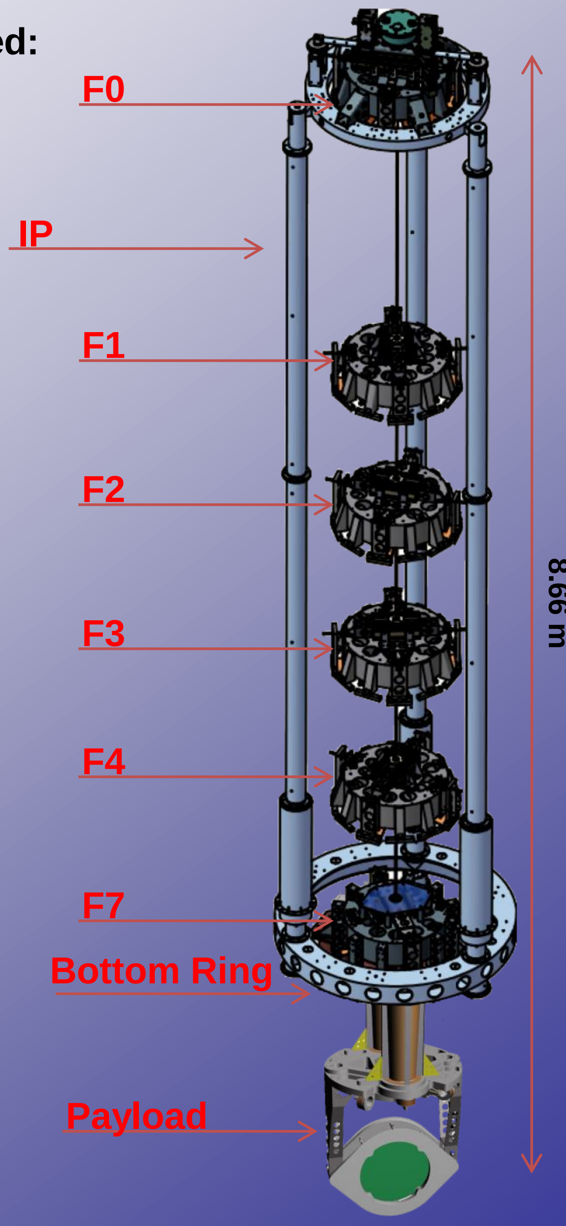




AdVirgo Superattenuator
Control system setup

On long superattenuators (BS, NI, NE, WI, WE, PR, SR) are installed:

- **18 LVDTs** of 3 different types
  - 9 Vertical LVDTs (F0 – F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT
  - 6 F7 LVDTs
- **5 Accelerometers** of 2 different types installed on F0:
  - 3 Horizontal Accs
  - 2 Vertical Accs
- **23 Coils** of 4 different types
  - 5 F0 Coils
  - 6 F7 Coils
  - 8 Marionette coils
  - 4 Mirror coils
- **3 Piezos** on bottom ring
- **21 Motors**
  - 1 Top screw F0 vertical motor
  - 3 F0 trolley motors
  - 6 Fishing rod motors
  - 2 Marionette motors
  - 4 F7 motors
  - 5 Accelerometer motors



AdVirgo Superattenuator

Control sytem hardware

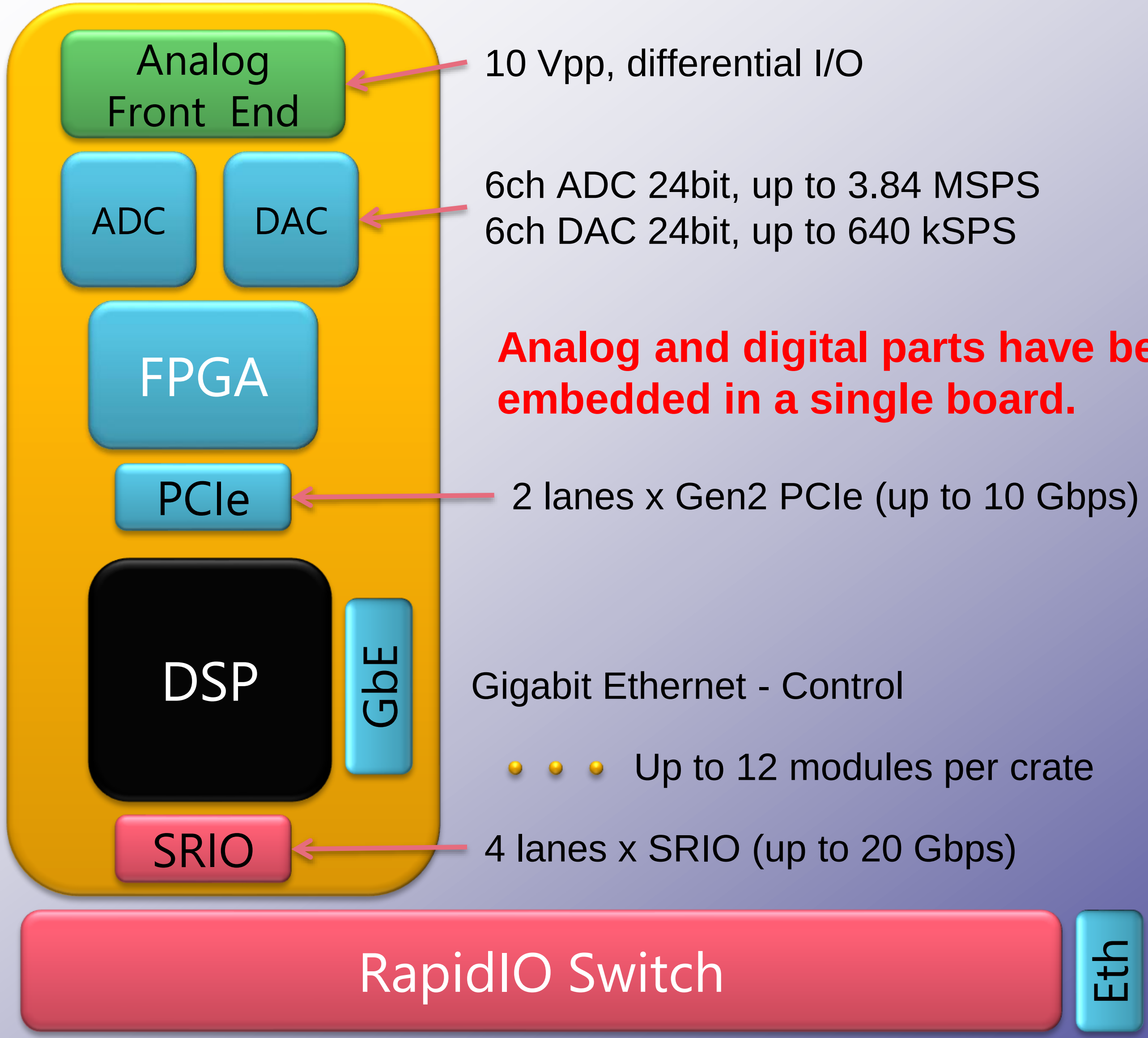
- **Electronics Design based on Texas Instruments DSP**
  - TMS320C6678
    - Eight TMS320C66x DSP Core Subsystems
    - 320 GMAC/160 GFLOP @ 1.25GHz
    - Four Lanes of SRIO 2.1 - 5 Gbaud Per Lane Full Duplex
    - Two Lanes PCIe Gen2 - 5 Gbaud Per Lane Full Duplex
    - Ethernet MAC Subsystem - Two SGMII Ports w/ 10/100/1000 Mbps operation
    - 64-Bit DDR3 Interface (DDR3-1600)

Computing power of a high-end GPU but extremely energy efficient and specifically designed for hard real-time applications

Platform		Effective Time to complete 1024 complex to complex FFT (single precision) μs	Power (Watts)	Energy per FFT (μJ)
GPU	nVidia Tesla C2070	0.16	225	36
GPU	nVidia Tesla C1060	0.3	188	56.4
GPP	Intel Xeon Core Duo @ 3 GHz	1.8	95	171
GPP	Intel Nehalam Quad Core @ 3.2 GHz	1.2	130	156
DSP	TI C6678 @ 1.2 GHz	0.86	10	8.6

AdVirgo Superattenuator

Control system hardware



10 Vpp, differential I/O

6ch ADC 24bit, up to 3.84 MSPS
6ch DAC 24bit, up to 640 kSPS

Analog and digital parts have been embedded in a single board.

2 lanes x Gen2 PCIe (up to 10 Gbps)

Gigabit Ethernet - Control

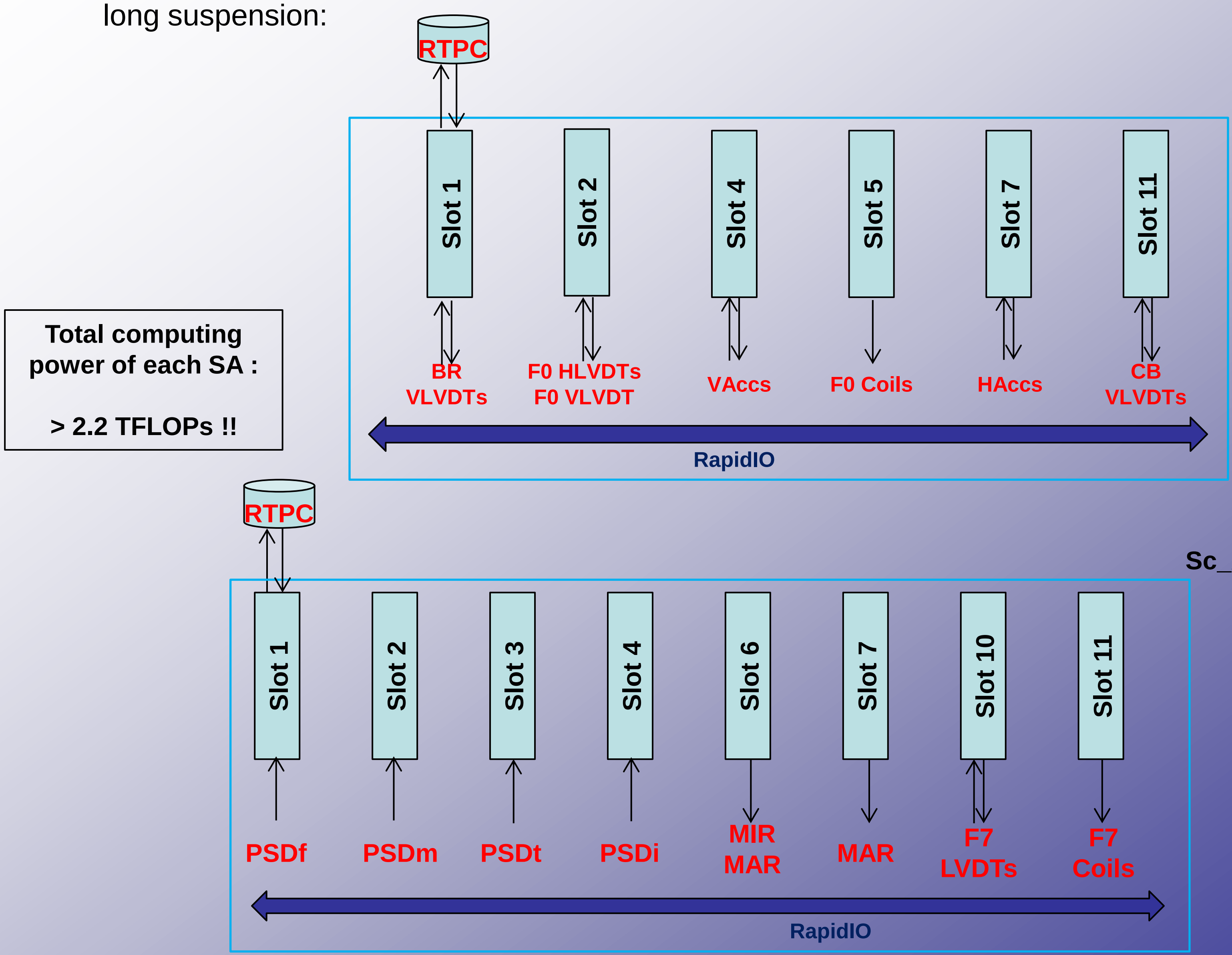
• • • Up to 12 modules per crate

4 lanes x SRIO (up to 20 Gbps)

100baseT - Management

AdVirgo Superattenuator
Control system hardware

• A total of 14 boards, each one equipped with an 8-core TMS320C6678 DSP, are connected to each long suspension:



AdVirgo Superattenuator
Control system software

SA control is an extremely complex system:

- **131** DSP boards are installed on BPC, BS, IB, MC, PR, NI, NE, WI, WE, SR, OB
- **185** control code files are running at the same time on the DSP cores at 10 kHz (IP, F7, LC controls), 40 kHz (Global signals oversampling) and 320 kHz (Digital demodulation of sensors)

- All the DSP software (code, generated assembler and binaries) is archived in an SVN repo that can be browsed: **https://svn.ego-gw.it/svn/satsw/DSPCode_Adv/**

O2 SOFTWARE MAP

SA	BOARD IP	CONNECTED DEVICES	SOFTWARE RUNNING (Core4, 10 kHz)	SOFTWARE RUNNING (Core1, 320 kHz)
BPC	172.16.2.104	PSD	/virgoDev/Sa/DSPCode_Adv/BPC/BPC_PSD	
BPC	172.16.2.141	PIEZO	/virgoDev/Sa/DSPCode_Adv/BPC/BPC_CD	
Sa_BS	172.16.2.62	BR LVDTs	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_MASTER	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_BR_LVDT_Demod
Sa_BS	172.16.2.53	F0 LVDTs	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_LVDT_HG_SRIO	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_LVDT_HG2
Sa_BS	172.16.2.32	F0 VAccs	/virgoDev/Sa/DSPCode_Adv/BS/Accs/BS_vAcc_LQG	/virgoDev/Sa/DSPCode_Adv/BS/Accs/BS_vAcc_Demod
Sa_BS	172.16.2.33	F0 Coils	/virgoDev/Sa/DSPCode_Adv/BS/InertialDamping/BS_ID_Diag	
Sa_BS	172.16.2.133	F0 HAccs	/virgoDev/Sa/DSPCode_Adv/BS/Accs/BS_Acc_LQG	/virgoDev/Sa/DSPCode_Adv/BS/Accs/BS_Acc_Demod
Sa_BS	172.16.2.52	F1-F7 VLVDTs	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_VLVDT_SRIO	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_VLVDT
Sc_BS	172.16.2.80	PSD	/virgoDev/Sa/DSPCode_Adv/BS/LC/BS_PSDf	
Sc_BS	172.16.2.108	PSD	/virgoDev/Sa/DSPCode_Adv/BS/LC/BS_PSDm	
Sc_BS	172.16.2.110	PSD	/virgoDev/Sa/DSPCode_Adv/BS/LC/BS_PSDt	
Sc_BS	172.16.2.84	PSD	/virgoDev/Sa/DSPCode_Adv/BS/LC/BS_PSDi	
Sc_BS	172.16.2.181	MIR, MAR Coils	/virgoDev/Sa/DSPCode_Adv/BS/LC/BS_Mir	
Sc_BS	172.16.2.179	MAR Coils	/virgoDev/Sa/DSPCode_Adv/BS/LC/BS_Mar	
Sc_BS	172.16.2.139	F7 LVDT	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_F7_LVDT	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_F7_LVDT_Demod
Sc_BS	172.16.2.120	F7 Coils	/virgoDev/Sa/DSPCode_Adv/BS/F7/BS_F7_CD	
Sa_IB	172.16.2.28	BR LVDTs	/virgoDev/Sa/DSPCode_Adv/IB/LVDT/IB_MASTER	/virgoDev/Sa/DSPCode_Adv/IB/LVDT/IB_BR_LVDT_Demod
Sa_IB	172.16.2.130	F0, F4, F7 LVDTs	/virgoDev/Sa/DSPCode_Adv/IB/LVDT/IB_LVDT	/virgoDev/Sa/DSPCode_Adv/IB/LVDT/IB_LVDT_Demod
Sa_IB	172.16.2.9	F0 VAccs	/virgoDev/Sa/DSPCode_Adv/IB/Accs/IB_vAcc_LQG	/virgoDev/Sa/DSPCode_Adv/IB/Accs/IB_vAcc_Demod
Sa_IB	172.16.2.121	F0 Coils	/virgoDev/Sa/DSPCode_Adv/IB/InertialDamping/IB_ID_Diag	
Sa_IB	172.16.2.23	F0 HAccs	/virgoDev/Sa/DSPCode_Adv/IB/Accs/IB_Acc_LQG	/virgoDev/Sa/DSPCode_Adv/IB/Accs/IB_Acc_Demod
Sc_IB	172.16.2.118	PSD	/virgoDev/Sa/DSPCode_Adv/IB/LC/IB_PSDf	
Sc_IB	172.16.2.86	PSD	/virgoDev/Sa/DSPCode_Adv/IB/LC/IB_PSDi	
Sc_IB	172.16.2.107	PSD	/virgoDev/Sa/DSPCode_Adv/IB/LC/IB_PSDt	
Sc_IB	172.16.2.173	MAR Coils	/virgoDev/Sa/DSPCode_Adv/IB/LC/IB_Mar1	
Sc_IB	172.16.2.174	MAR Coils	/virgoDev/Sa/DSPCode_Adv/IB/LC/IB_Mar2	
Sa_MC	172.16.2.128	BR LVDTs	/virgoDev/Sa/DSPCode_Adv/MC/LVDT/MC_MASTER	/virgoDev/Sa/DSPCode_Adv/MC/LVDT/MC_BR_LVDT_Demod
Sa_MC	172.16.2.51	F0, F4, F7 LVDTs	/virgoDev/Sa/DSPCode_Adv/MC/LVDT/MC_LVDT	/virgoDev/Sa/DSPCode_Adv/MC/LVDT/MC_LVDT_Demod
Sa_MC	172.16.2.158	F0 VAccs	/virgoDev/Sa/DSPCode_Adv/MC/Accs/MC_vAcc_LQG	/virgoDev/Sa/DSPCode_Adv/MC/Accs/MC_vAcc_Demod
Sa_MC	172.16.2.103	F0 Coils	/virgoDev/Sa/DSPCode_Adv/MC/InertialDamping/MC_ID_Diag	
Sa_MC	172.16.2.14	F0 HAccs	/virgoDev/Sa/DSPCode_Adv/MC/Accs/MC_Acc_LQG	/virgoDev/Sa/DSPCode_Adv/MC/Accs/MC_Acc_Demod
Sa_MC	172.16.2.150	PIEZO	/virgoDev/Sa/DSPCode_Adv/MC/Tilt/Piezo_Test	
Sc_MC	172.16.2.101	PSD	/virgoDev/Sa/DSPCode_Adv/MC/LC/MC_PSDf	
Sc_MC	172.16.2.168	PSD	/virgoDev/Sa/DSPCode_Adv/MC/LC/MC_PSDi	
Sc_MC	172.16.2.88	PSD	/virgoDev/Sa/DSPCode_Adv/MC/LC/MC_PSDTf	
Sc_MC	172.16.2.109	PSD	/virgoDev/Sa/DSPCode_Adv/MC/LC/MC_PSDTi	
Sc_MC	172.16.2.171	MAR Coils	/virgoDev/Sa/DSPCode_Adv/MC/LC/MC_Mar1	
Sc_MC	172.16.2.172	MAR Coils	/virgoDev/Sa/DSPCode_Adv/MC/LC/MC_Mar2	
Sc_MC	172.16.2.176	MIR Coils	/virgoDev/Sa/DSPCode_Adv/MC/LC/MC_Mir	
Sa_NE	172.16.2.37	BR LVDTs	/virgoDev/Sa/DSPCode_Adv/NE/LVDT/NE_MASTER	/virgoDev/Sa/DSPCode_Adv/NE/LVDT/NE_BR_LVDT_Demod
Sa_NE	172.16.2.40	F0 LVDTs	/virgoDev/Sa/DSPCode_Adv/NE/LVDT/NE_LVDT	/virgoDev/Sa/DSPCode_Adv/NE/LVDT/NE_LVDT_Demod

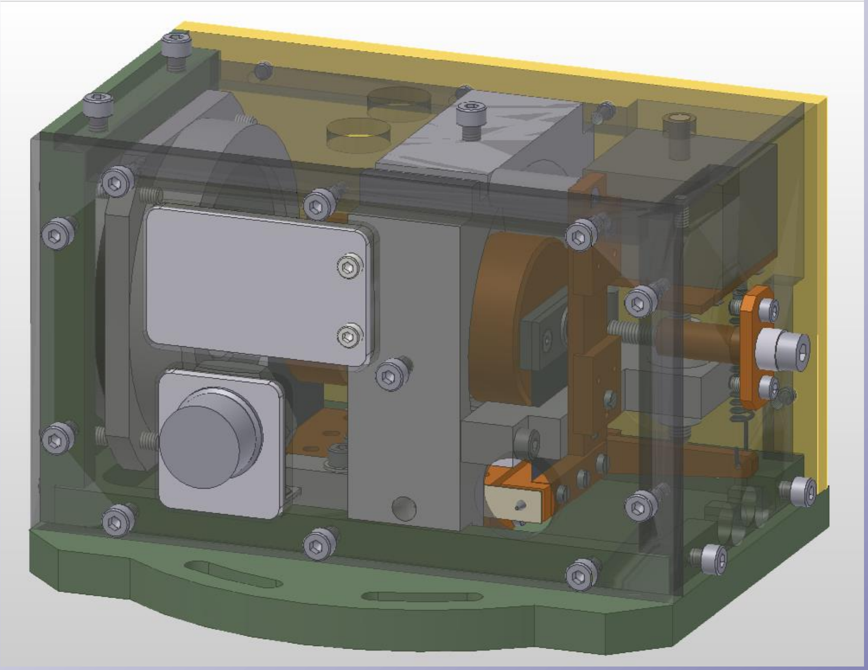
⋮

AdVirgo Superattenuator
Sensors

- There is a total of 5 Accelerometer (Accs) installed on the suspension F0 of 2 different types with sensitivity of about $3*10^{-10}$ m/s^2/sqrt(Hz) for f < 3 Hz

- There are 18 LVDTs installed on long tower suspensions of 3 different types with a sensitivity of about 10^{-8} m/sqrt(Hz) for f > 0.1 Hz

- All the LVDTs are operated using a digital demodulation scheme at 320 kHz sampling frequency

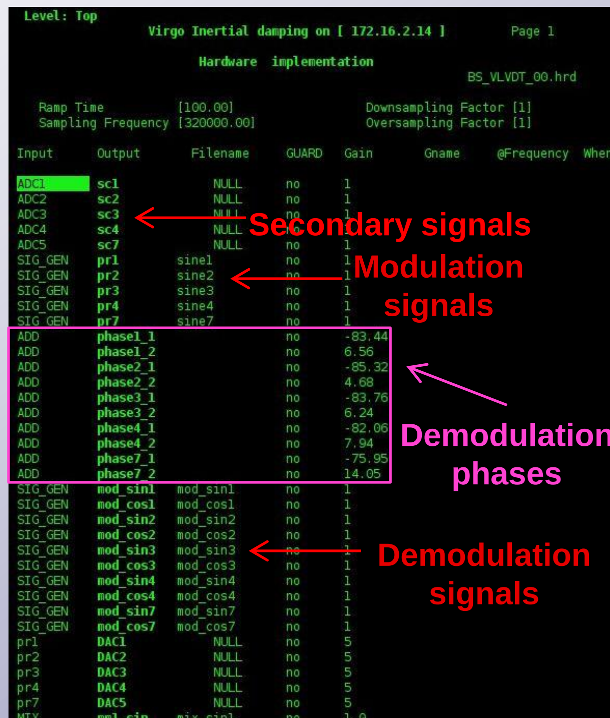


AdVirgo Superattenuator
Sensors

- There are 18 LVDTs installed on long tower suspensions of 3 different types
  - 9 Vertical LVDTs (F0 – F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT
  - 6 F7 LVDTs

- Each sensors have been characterized and calibrated

- All the LVDTs are operated using a digital demodulation scheme at 320 kHz sampling frequency:



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Virgo Inertial damping on [172.16.2.14] Page 1

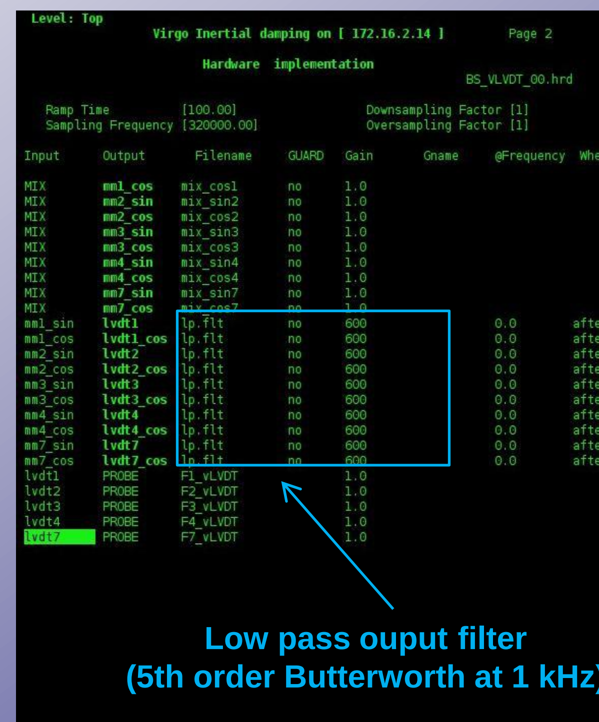
Hardware implementation

BS_VLVDT_00.hrd

Ramp Time [100.00] Downsampling Factor [1]

Sampling Frequency [320000.00] Oversampling Factor [1]

Input	Output	Filename	GUARD	Gain	Gname	@Frequency	When
ADC1	sc1	NULL	no	1			
ADC2	sc2	NULL	no	1			
ADC3	sc3	NULL	no	1			
ADC4	sc4	NULL	no	1			
ADC5	sc7	NULL	no	1			
SIG_GEN	pr1	sine1	no	1			
SIG_GEN	pr2	sine2	no	1			
SIG_GEN	pr3	sine3	no	1			
SIG_GEN	pr4	sine4	no	1			
SIG_GEN	pr7	sine7	no	1			
ADD	phase1_1		no	-83.44			
ADD	phase1_2		no	6.56			
ADD	phase2_1		no	-85.32			
ADD	phase2_2		no	4.68			
ADD	phase3_1		no	-83.76			
ADD	phase3_2		no	6.24			
ADD	phase4_1		no	-82.06			
ADD	phase4_2		no	7.94			
ADD	phase7_1		no	-75.95			
ADD	phase7_2		no	14.05			
SIG_GEN	mod_sin1	mod_sin1	no	1			
SIG_GEN	mod_cos1	mod_cos1	no	1			
SIG_GEN	mod_sin2	mod_sin2	no	1			
SIG_GEN	mod_cos2	mod_cos2	no	1			
SIG_GEN	mod_sin3	mod_sin3	no	1			
SIG_GEN	mod_cos3	mod_cos3	no	1			
SIG_GEN	mod_sin4	mod_sin4	no	1			
SIG_GEN	mod_cos4	mod_cos4	no	1			
SIG_GEN	mod_sin7	mod_sin7	no	1			
SIG_GEN	mod_cos7	mod_cos7	no	1			
pr1	DAC1	NULL	no	5			
pr2	DAC2	NULL	no	5			
pr3	DAC3	NULL	no	5			
pr4	DAC4	NULL	no	5			
pr7	DAC5	NULL	no	5			
MIX	mm1_sin	mix_sin1	no	1.0			



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Virgo Inertial damping on [172.16.2.14] Page 2

Hardware implementation

BS_VLVDT_00.hrd

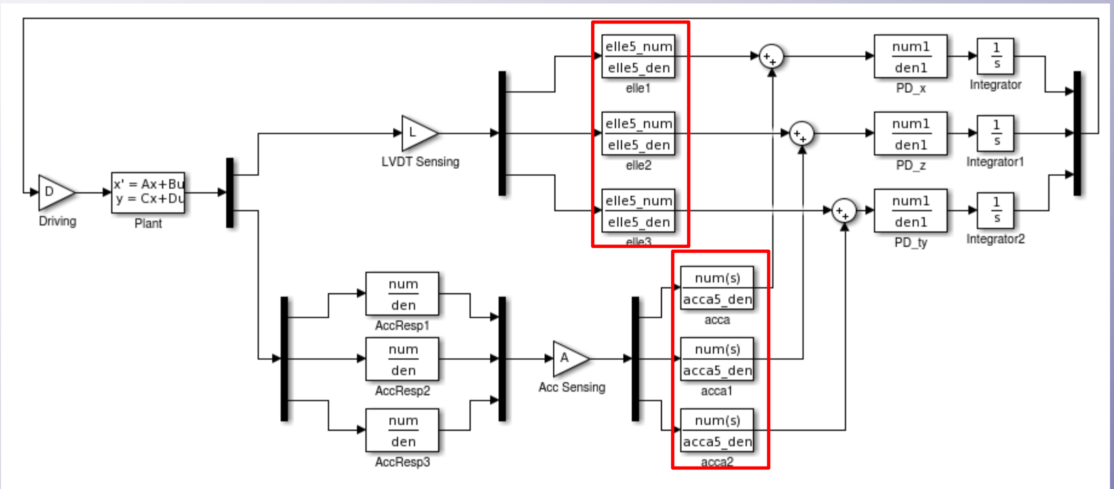
Ramp Time [100.00] Downsampling Factor [1]

Sampling Frequency [320000.00] Oversampling Factor [1]

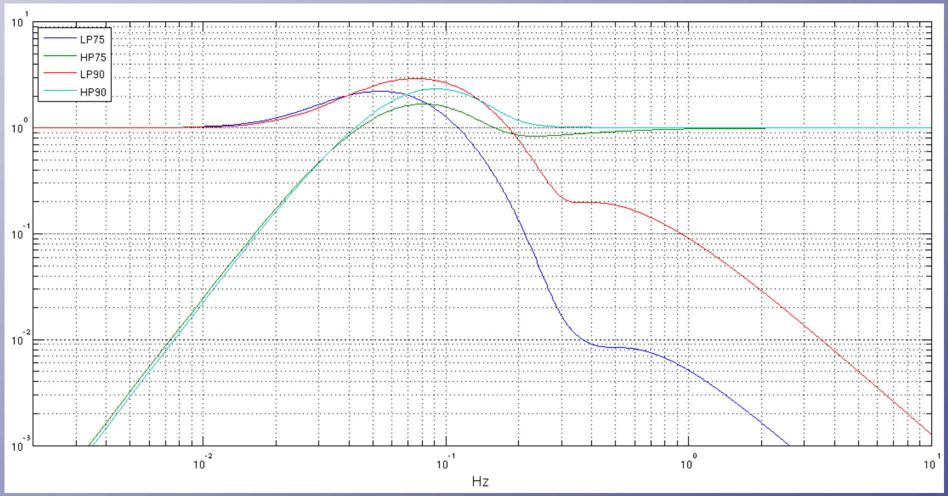
Input	Output	Filename	GUARD	Gain	Gname	@Frequency	When
MIX	mm1_cos	mix_cos1	no	1.0			
MIX	mm2_sin	mix_sin2	no	1.0			
MIX	mm2_cos	mix_cos2	no	1.0			
MIX	mm3_sin	mix_sin3	no	1.0			
MIX	mm3_cos	mix_cos3	no	1.0			
MIX	mm4_sin	mix_sin4	no	1.0			
MIX	mm4_cos	mix_cos4	no	1.0			
MIX	mm7_sin	mix_sin7	no	1.0			
MIX	mm7_cos	mix_cos7	no	1.0			
mm1_sin	lvdt1	lp.flt	no	600		0.0	after
mm1_cos	lvdt1_cos	lp.flt	no	600		0.0	after
mm2_sin	lvdt2	lp.flt	no	600		0.0	after
mm2_cos	lvdt2_cos	lp.flt	no	600		0.0	after
mm3_sin	lvdt3	lp.flt	no	600		0.0	after
mm3_cos	lvdt3_cos	lp.flt	no	600		0.0	after
mm4_sin	lvdt4	lp.flt	no	600		0.0	after
mm4_cos	lvdt4_cos	lp.flt	no	600		0.0	after
mm7_sin	lvdt7	lp.flt	no	600		0.0	after
mm7_cos	lvdt7_cos	lp.flt	no	600		0.0	after
lvdt1	PROBE	F1_vLVDT		1.0			
lvdt2	PROBE	F2_vLVDT		1.0			
lvdt3	PROBE	F3_vLVDT		1.0			
lvdt4	PROBE	F4_vLVDT		1.0			
lvdt7	PROBE	F7_vLVDT		1.0			

AdVirgo Superattenuator
Inertial Damping

Two Accelerometer-LVDT blending filters are used (High Pass for Accs and Low Pass for LVDTs)
- 75 mHz crossover frequency used for standard operation
- 90 mHz crossover frequency for robustness (High microseism or windy conditions)



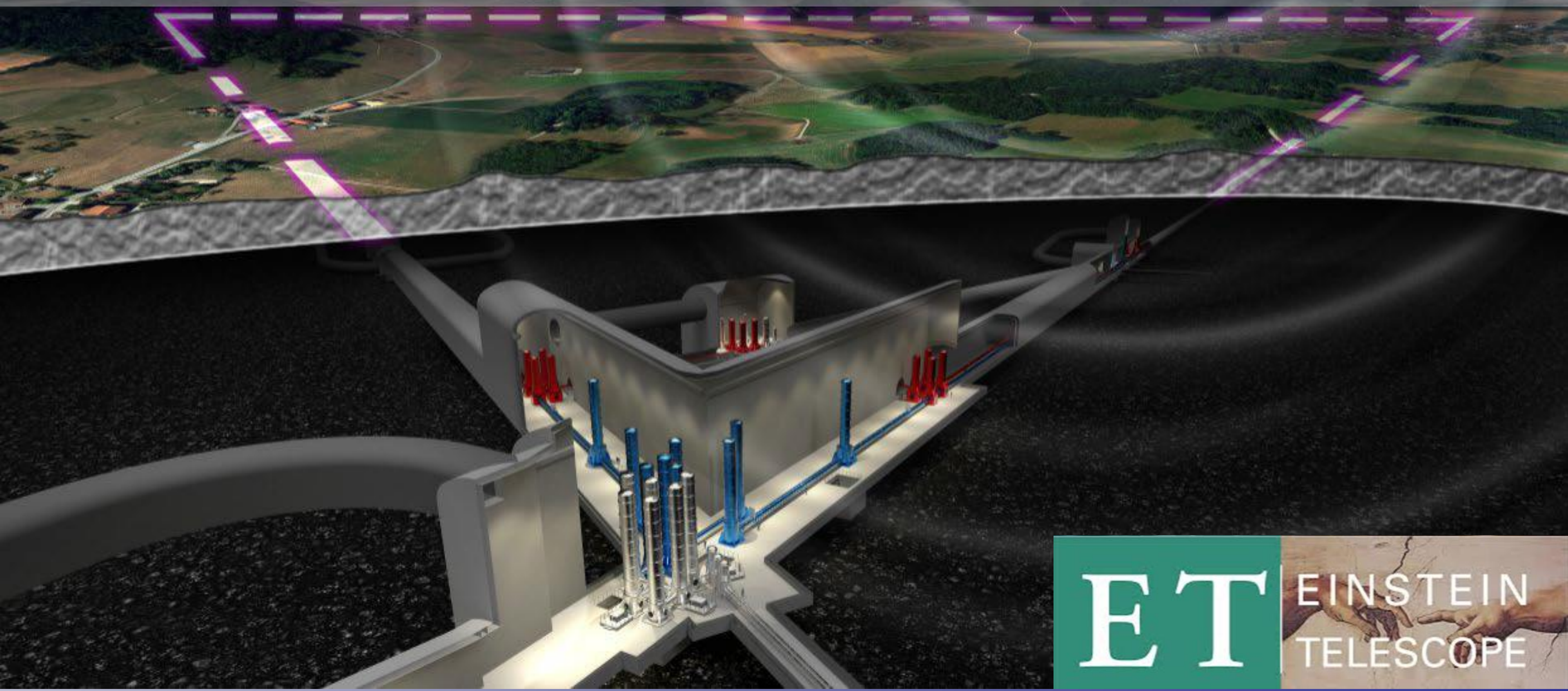
Standard Blending filters



The future of gravitational wave astronomy

Einstein Telescope

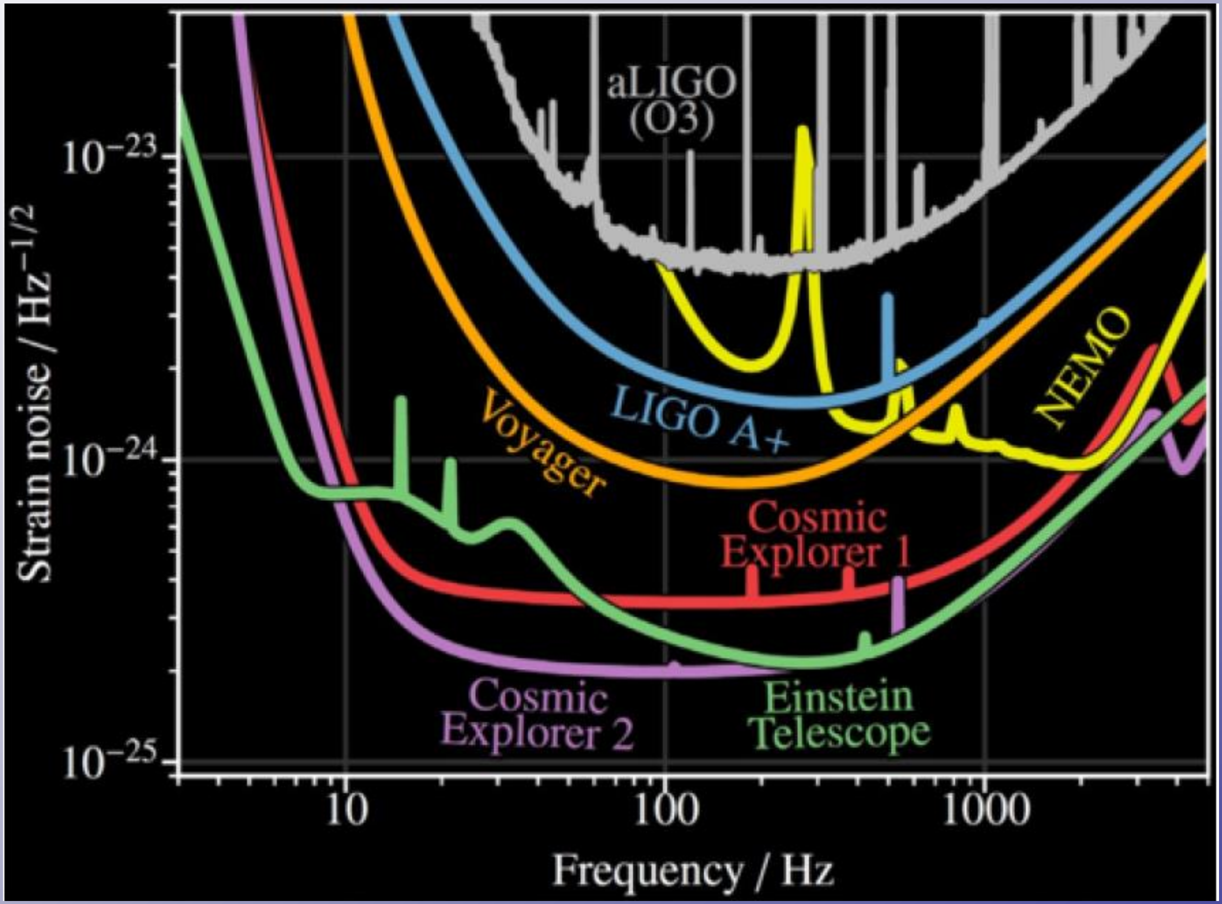
- Einstein Telescope (ET) is expected to have a triangular configuration, with 10 km of length for each side, in order to host two detectors with different bandwidths, and, to drastically reduce the effects of ground motion, will be built underground, making the needed infrastructural works very complex and expensive.
- In Europe three candidate sites have been identified for ET: an area in the Nuoro province, in Sardinia, Italy, the Meuse-Rhine euroregion at the border between Netherlands, Belgium and Germany, and a location in Saxony, Germany.



Einstein Telescope
Seismic isolation

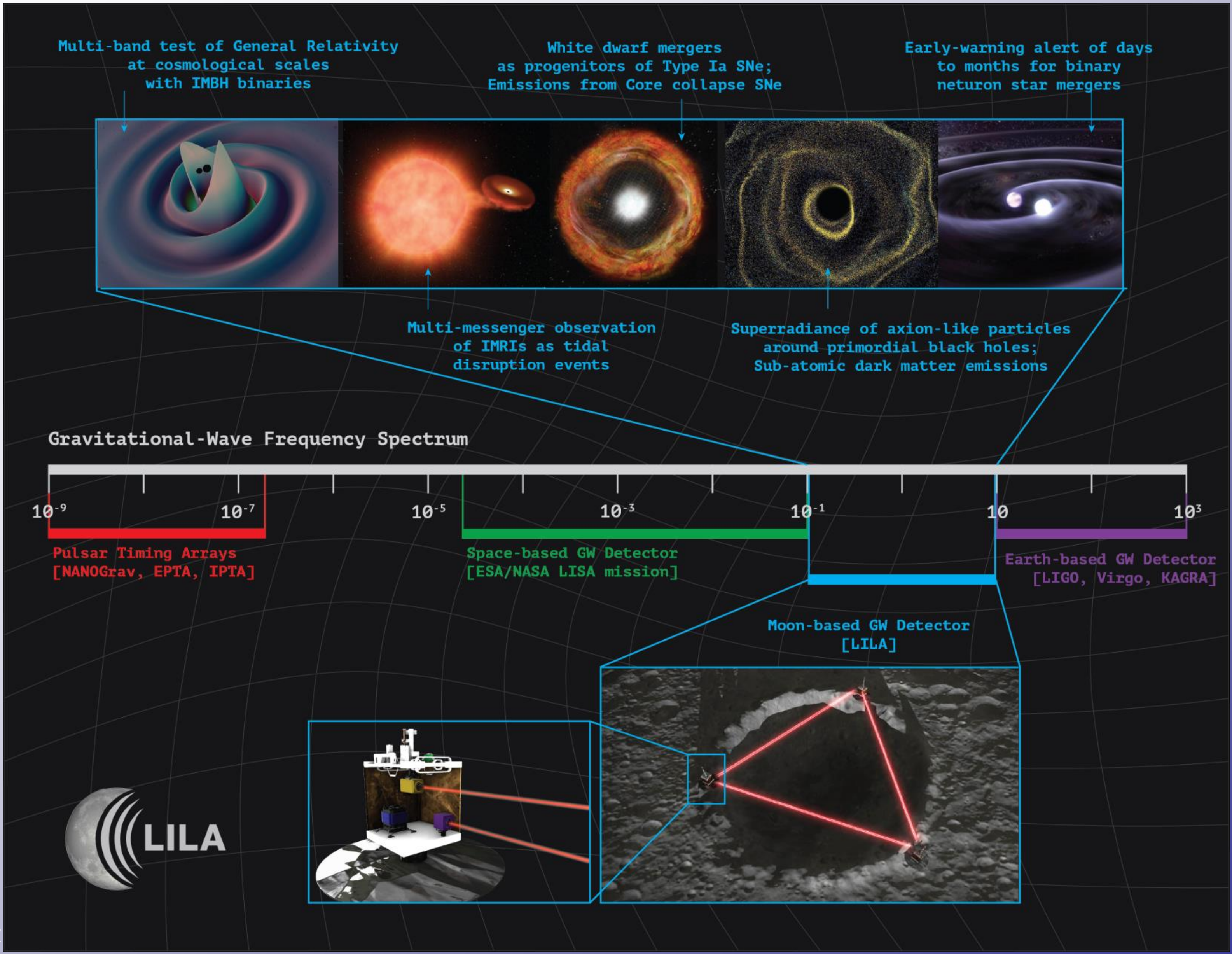
- The gravitational-wave interferometers of next generation, Einstein and Cosmic Explorer, aim at gaining a factor of 10 in noise level, respect to Virgo and LIGO, but also extending at low frequency their detection band.

- Even in a site with very low seismicity, the sensitivity increase in the low frequency region will put challenging constraints on the suppression of seismic noise: **new designs should be studied**.



Laser Interferometer Lunar Antenna

https://www.vanderbilt.edu/lunarlabs/lila/

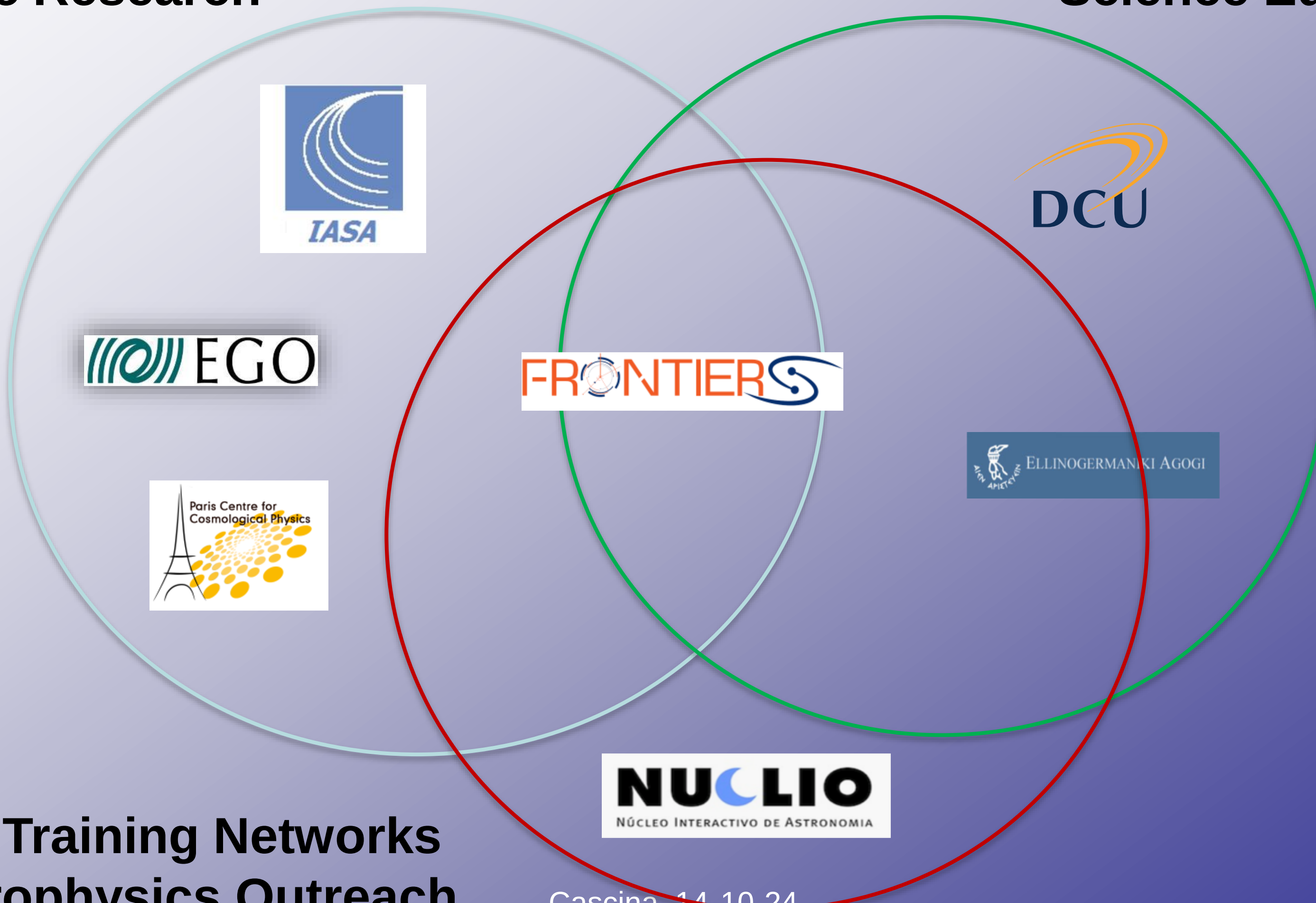


Frontiers (https://frontiers-project.eu/)

was an EU funded project bringing together **research** and **educational** institutions from all over **Europe** (2018-2021)

Scientific Research

Science Education



Teacher Training Networks and Astrophysics Outreach

Thank you for your attention!!