Suspension Control
AdVirgo+ Experience

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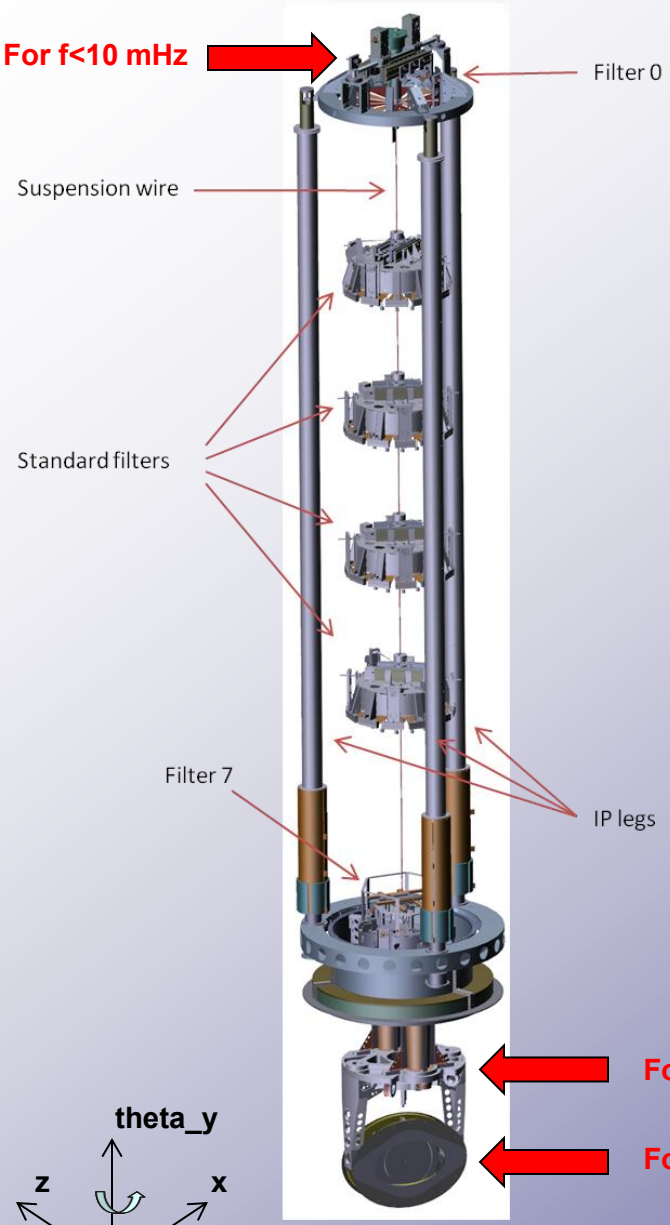
Introduction
Control system setup



The control system has been designed using a hierarchical strategy regulated by the dynamic range of the actuators.

- 23 Coil Magnet Actuators in 3 points (actuation stages) of the SA:

- **Filter 0**:
Large displacements (hundreds of microns) for f<10 mHz.
- **Filter 7 + Marionette**:
Small payload displacements (1 micron) in the 10 mHz<f<1 Hz band.
- **Filter 7 + Mirror**:
Small residual mirror displacements (a few nm), for f>1 Hz.

- **>**20 Local Sensors
- Accelerometers
- 4 Displacements Sensors (LVDTs) on Filter 0
- 6 Displacements Sensors on Filter 0
- Optical Readout of Marionette and Mirror Position

- Digital Control system based on high-performance multicore DSPs.

Introduction
Control system setup

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

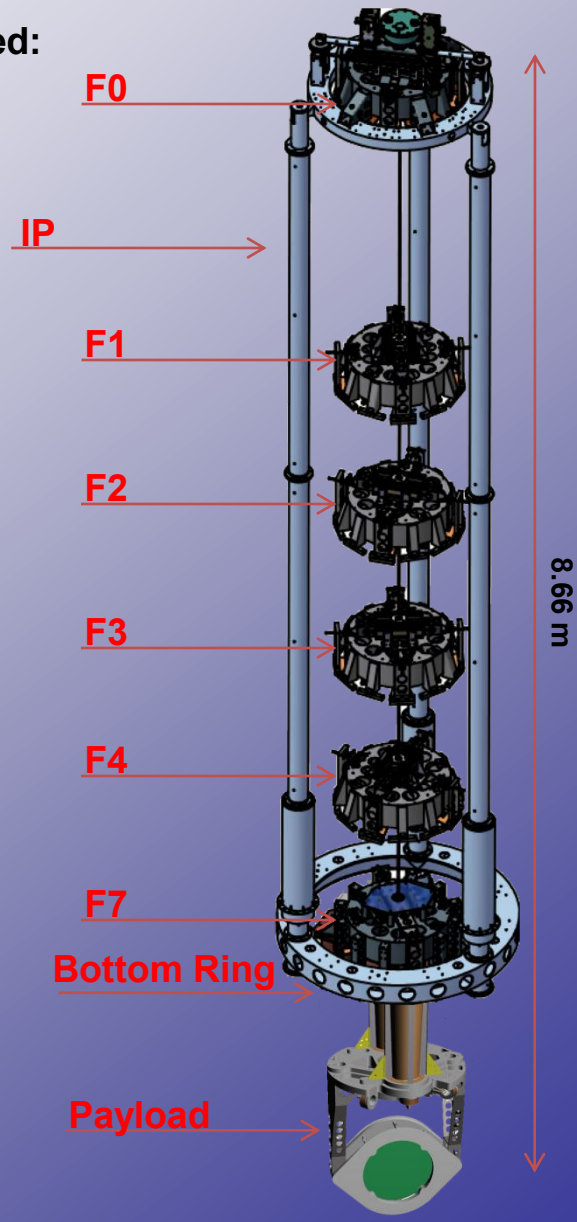
- **18 LVDTs** of 3 different types
  - 9 Vertical LVDTs (F0 – F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT
  - 6 F7 LVDTs

- **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 (**Not uset yet**)

- **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



Introduction
Control system setup

On IB superattenuator are installed:

- **9 LVDTs** of 2 different types
  - 6 Vertical LVDTs (F0, F4, F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT

- **5 Accelerometers** of 2 different types installed on F0:
  - 3 Horizontal Accs
  - 2 Vertical Accs

- **13 Coils** of 2 different types
  - 5 F0 Coils
  - 8 Marionette coils

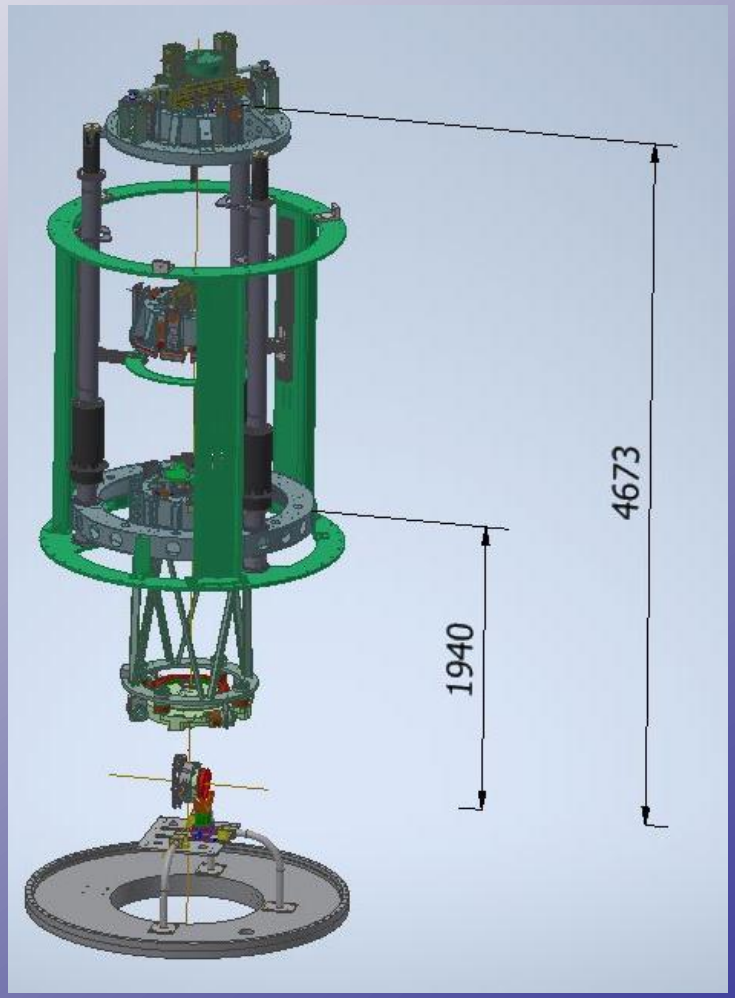
- **3 Piezos** on bottom ring (**Not used yet**)

- **18 Motors**
  - 1 Top screw F0 vertical motor
  - 3 F0 trolley motors
  - 3 Fishing rod motors
  - 2 Marionette motors
  - 4 F7 motors
  - 5 Accelerometer motors

Introduction
Control system setup

On MC superattenuator are installed:

- **9 LVDTs** of 2 different types
  - 6 Vertical LVDTs (F0, F4, F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT
- **5 Accelerometers** of 2 different types installed on F0:
  - 3 Horizontal Accs
  - 2 Vertical Accs
- **17 Coils** of 3 different types
  - 5 F0 Coils
  - 8 Marionette Coils
  - 4 Mirror Coils
- **3 Piezos** on bottom ring (**Not used yet**)
- **19 Motors**
  - 1 Top screw F0 vertical motor
  - 3 F0 trolley motors
  - 4 Fishing rod motors
  - 2 Marionette motors
  - 4 F7 motors
  - 5 Accelerometer motors



Introduction
Control system setup

On detection (SDB1) superattenuator (OB) are installed:

- **9 LVDTs** of 3 different types
  - 6 Vertical LVDTs (F0, F4, F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT

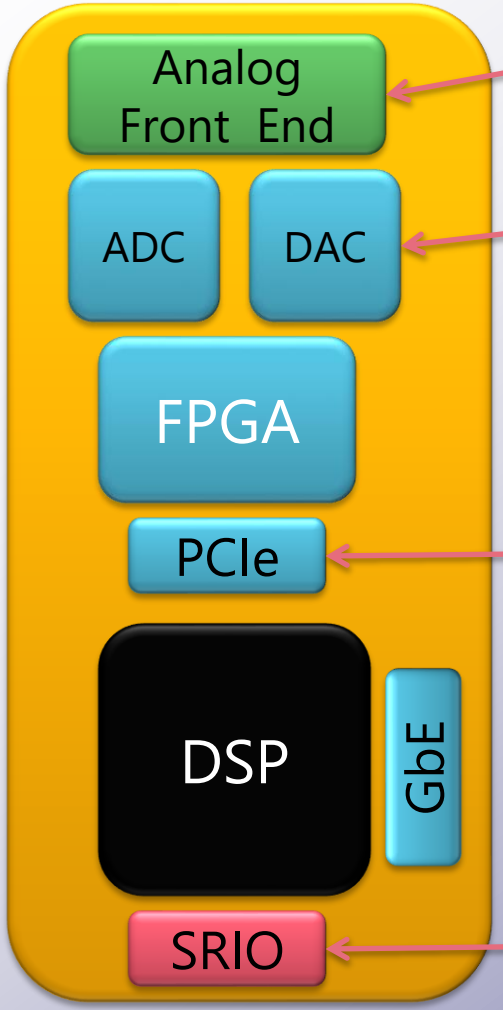
- **5 Accelerometers** of 2 different types installed on F0:
  - 3 Horizontal Accs
  - 2 Vertical Accs

- **5 F0 Coils**

- **3 Piezos** on bottom ring (**Not used yet**)

- **18 Motors**
  - 1 Top screw F0 vertical motor
  - 3 F0 trolley motors
  - 3 Fishing rod motors
  - 2 Marionette motors
  - 4 F7 motors
  - 5 Accelerometer motors

Introduction
Control system setup



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

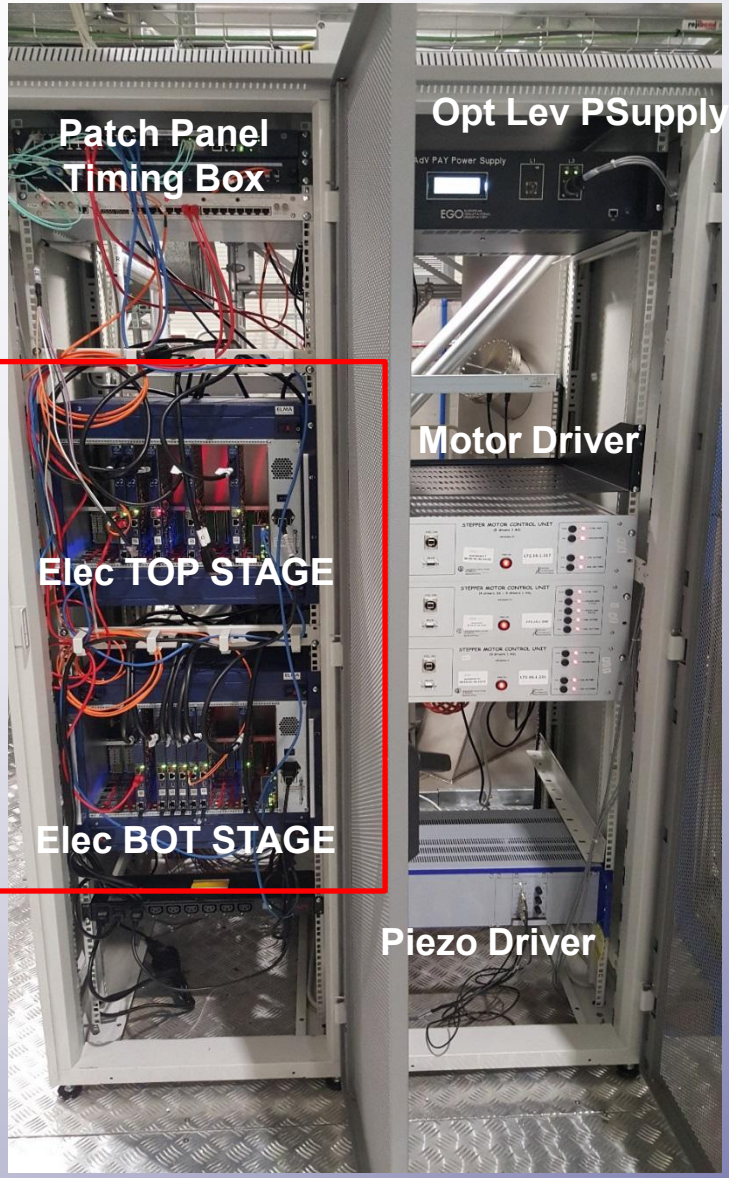
4 lanes x SRIO (up to 20 Gbps)

RapidIO Switch

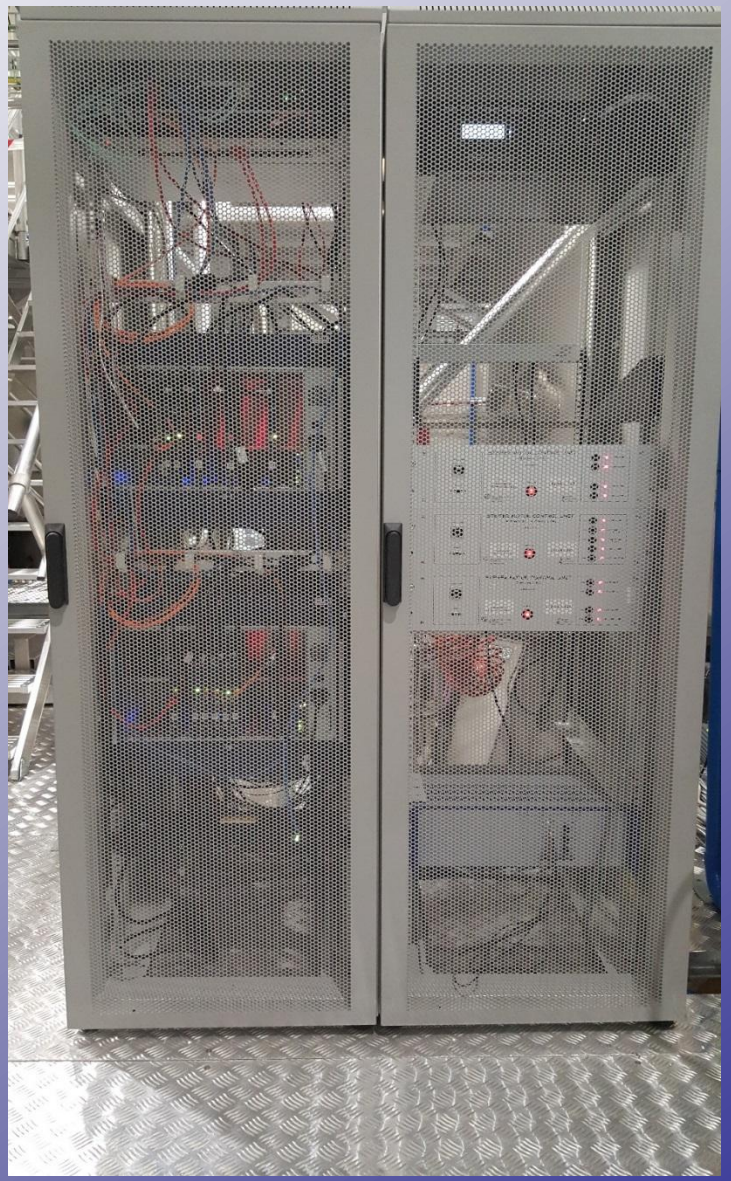
Eth

100baseT - Management

Introduction
Control system setup

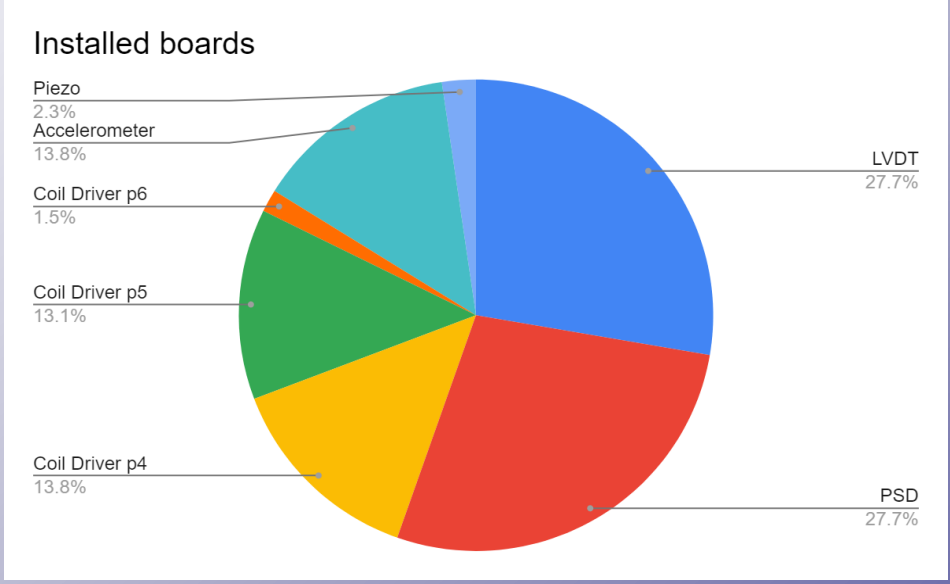


NI Tower



Introduction
Control system setup

- There is a total of 130 DSP boards in SAT, PAY, INJ of 7 alternative configurations depending on their use:
  - **LVDT**: digital demodulation of horizontal and vertical LVDTs of F0 and F7.
  - **Accelerometer**: LVDT digital demodulation and control of the sensing element of both horizontal and vertical F0 accelerometers.
  - **PSD**: signal acquisition of mirror (PSDf, PSDi) and marionette (PSDm, PSDt) optical lever PSDs.
  - **Coil Driver p4**: the board is equipped with TI OPA544 operational amplifier and is used for F0 and F7 actuation. The opamp is capable of erogating a peak current of 310 mA.
  - **Coil Driver p5**: the board is equipped with AD8397 operational amplifier and is used for mirror and marionette high power actuation. The opamp is capable of erogating a peak current of 2 A. This board type has been produced in limited quantities (20 samples).
  - **Coil Driver p6**: the board is equipped with analog shaping filters, TI OPA1612 operational amplifiers and it is used for NE and WE low noise mirror actuation. The opamp is capable of erogating a peak current of 40 mA.
  - **Piezo**: driving of bottom ring piezoelectric actuators.

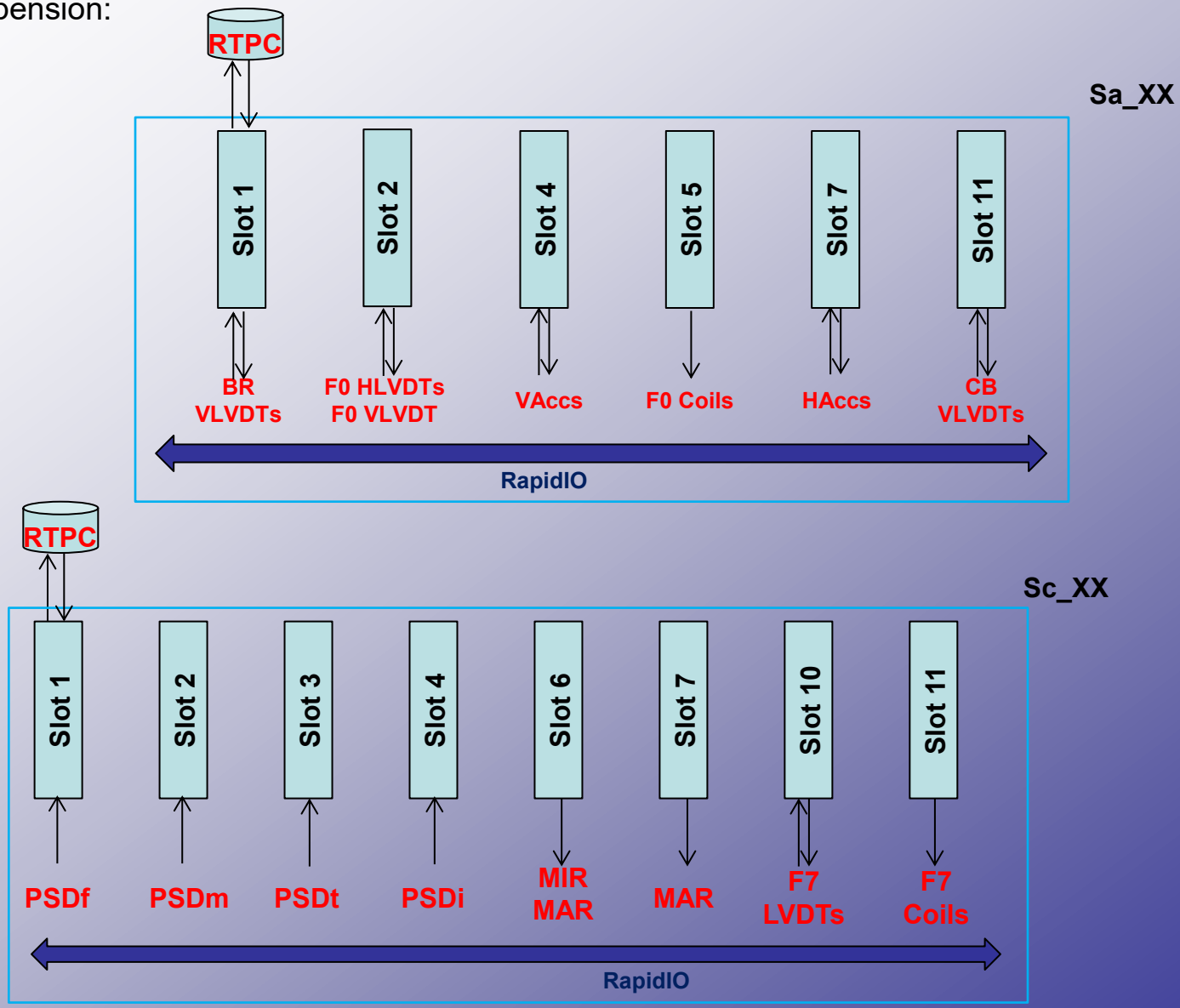


Electronic board name	Installed Boards	% (P_i)
LVDT	36	28
PSD	36	28
Coil Driver p4	18	14
Coil Driver p5	17	13
Coil Driver p6	2	2
Accelerometer	18	14
Piezo	3	2
Total	130	

Introduction

Control system setup

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



Introduction
Control system setup

SA control is an extremely complex system:

- **130** 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

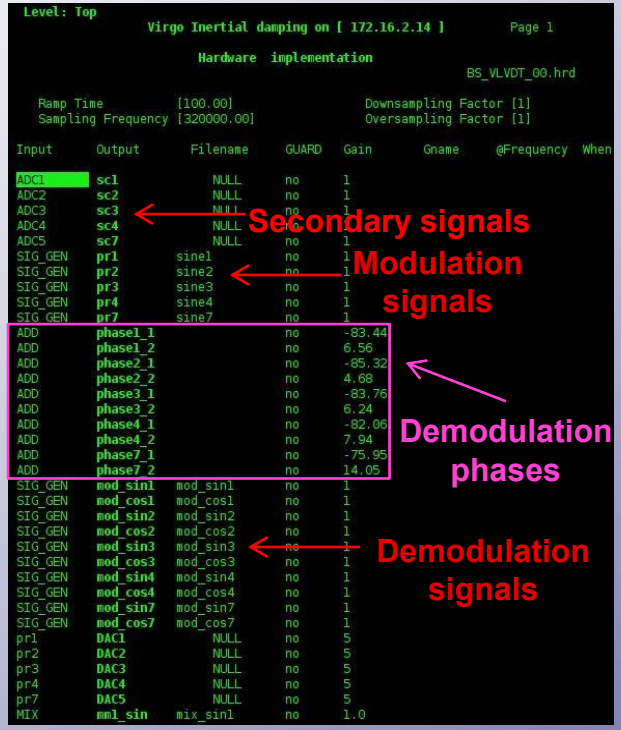
SA	BOARD IP	CONNECTED DEVICES	SOFTWARE RUNNING (Core4, 10 kHz)	SOFTWARE RUNNING (Core1, 320 kHz)
BPC	172.16.2.104	PSD	/virgoDev/Sa/DSPCode_Adv/BPC/BPC_PSD	
BPC	172.16.2.141	PIEZO	/virgoDev/Sa/DSPCode_Adv/BPC/BPC_CD	
Sa_BS	172.16.2.62	BR LVDTs	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_MASTER	/virgoDev/Sa/DSPCode_Adv/BS/LVDT/BS_BR_LVDT_Demod
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

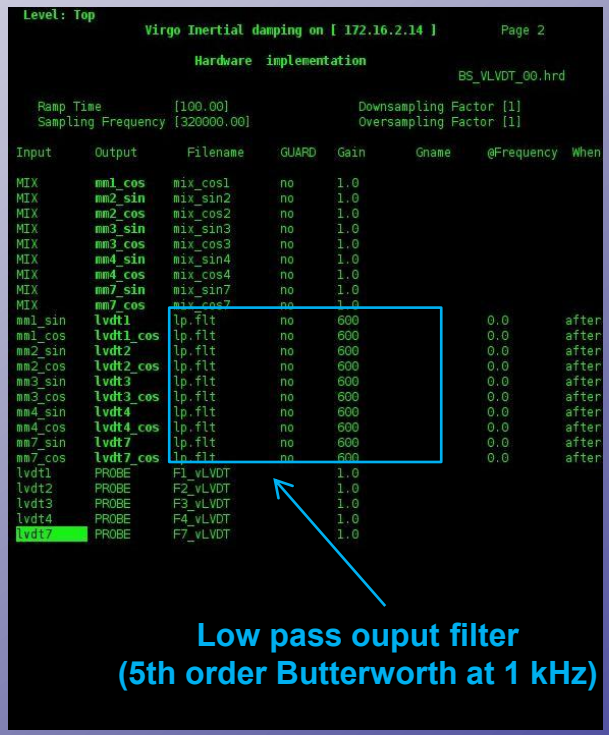
Sensors
LVDTs

- 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:

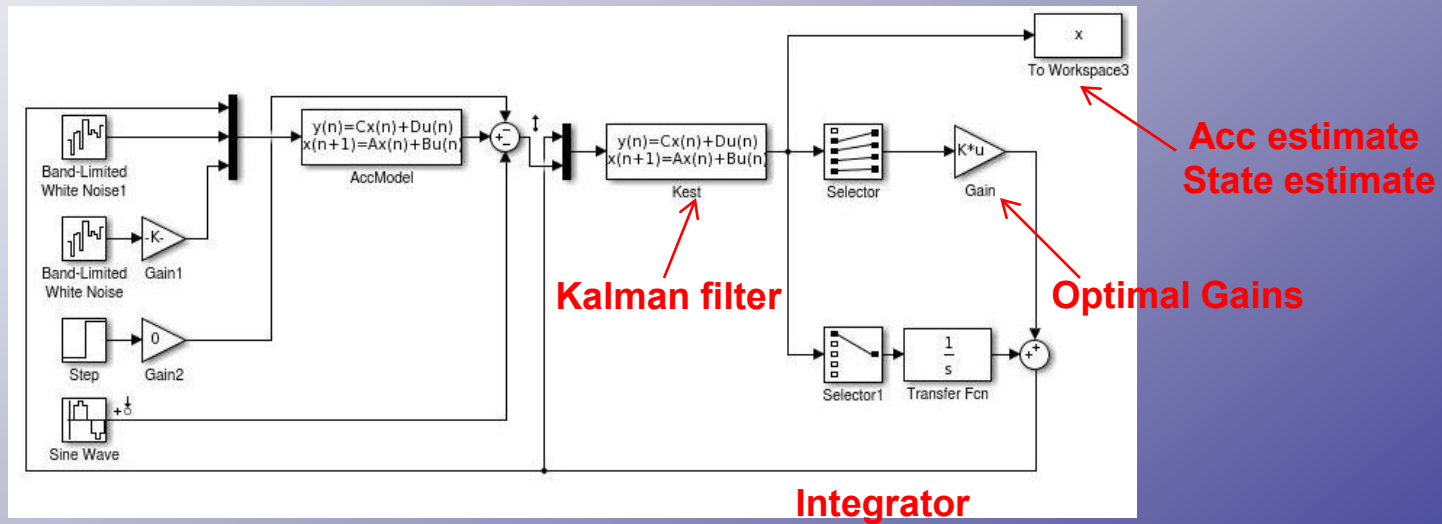




Sensors
Accelerometers

- There is a total of 5 Accelerometer (Accs) installed on the suspension F0 of 2 different types
  - 3 Horizontal Accs
  - 2 Vertical Accs

- A model of the sensor mechanics and its disturbances has been developed in order to design the Kalman estimator and the controller.



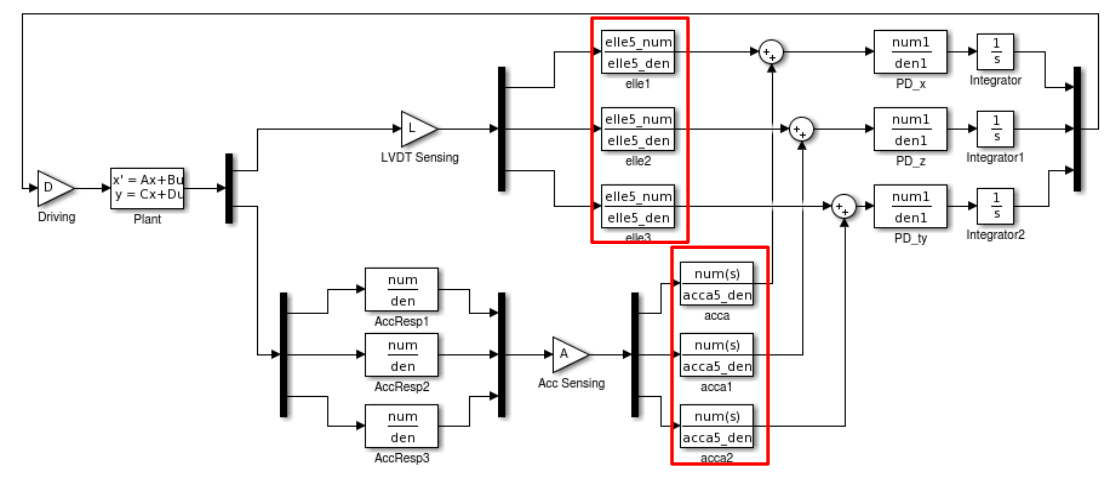
Inertial Damping
Overview

- **Two loops based on traditional sensor blending are currently used to control IP motion**:

Horizontal Inertial Damping (ty, x, z)

6 x 3 plant matrix:
(3 LVDTs + 3 Accelerometers) x 3 Coils on filter 0

3 x 3 Diagonalized Control matrix

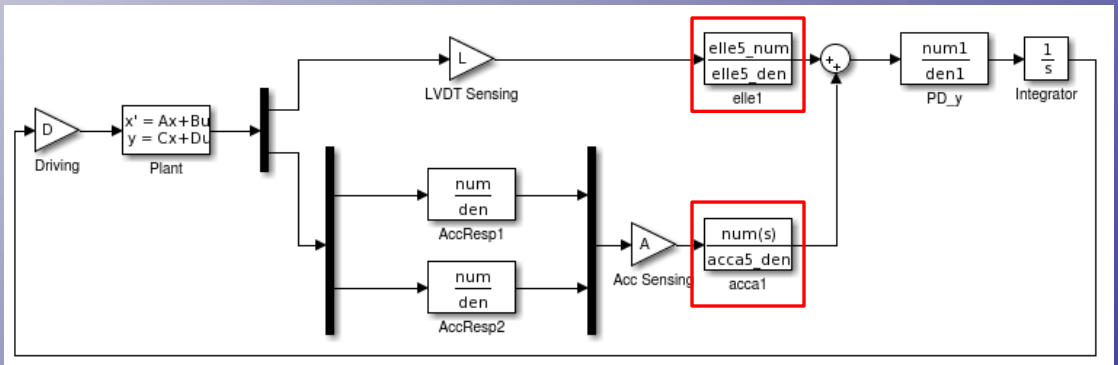


Blending filters

Vertical Inertial Damping (y)

3 x 2 control matrix:
(1 LVDTs + 2 Accelerometers) x 2 Coils on filter 0

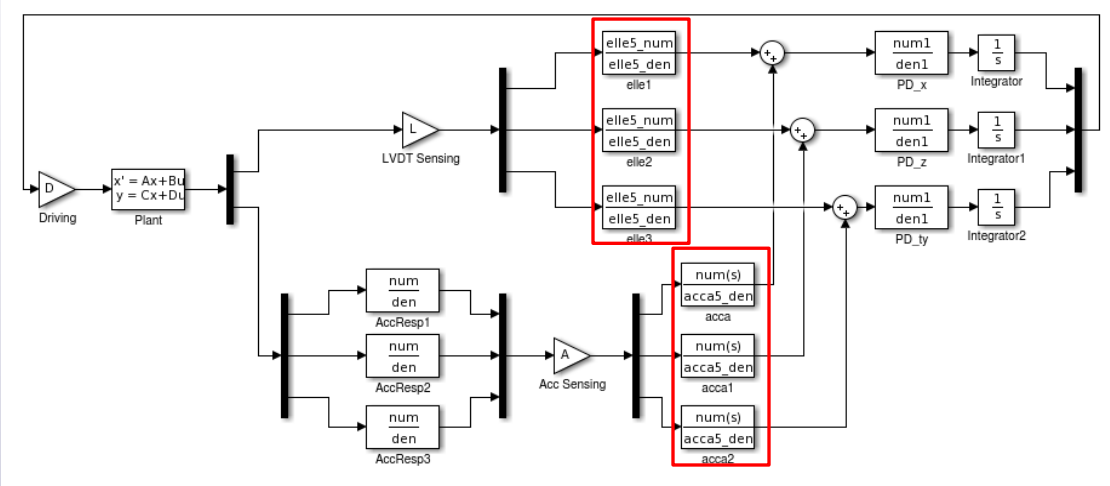
1 x 2 Diagonalized Control matrix



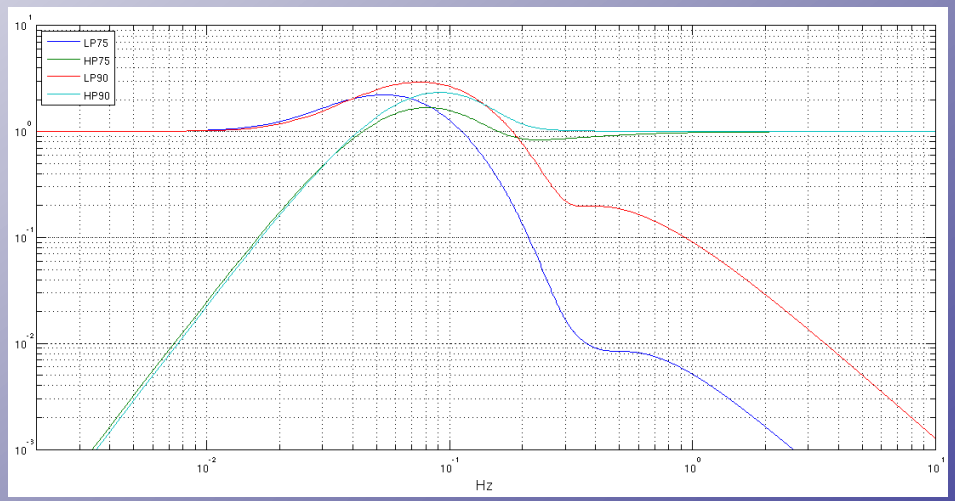
Inertial Damping
Standard Blending

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

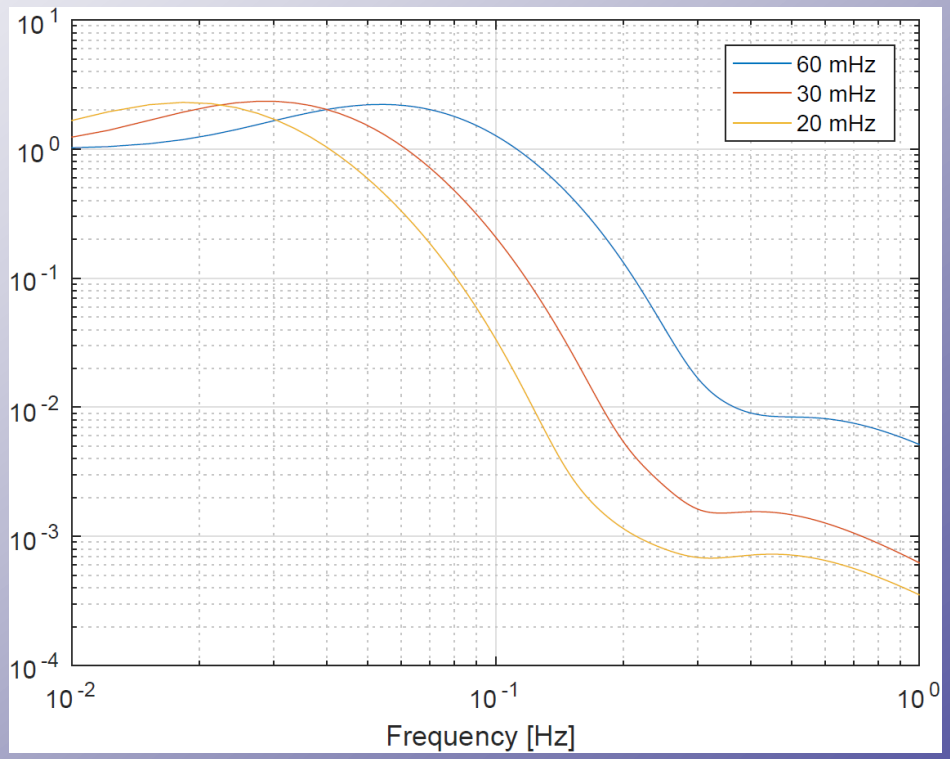


Inertial Damping
GIPC

- Global Inverted Pendulum Control (GIPC) is a technique already used in VIRGO in which common and differential error signals are used to control the IP top stage instead of the local LVDTs and Accelerometers

- Using this strategy the crossover frequency of the blending filters can be lowered (20 mHz, 30 mHz) without losing robustness improving the rejection of microseism.

Accelerometer low-pass filter comparison



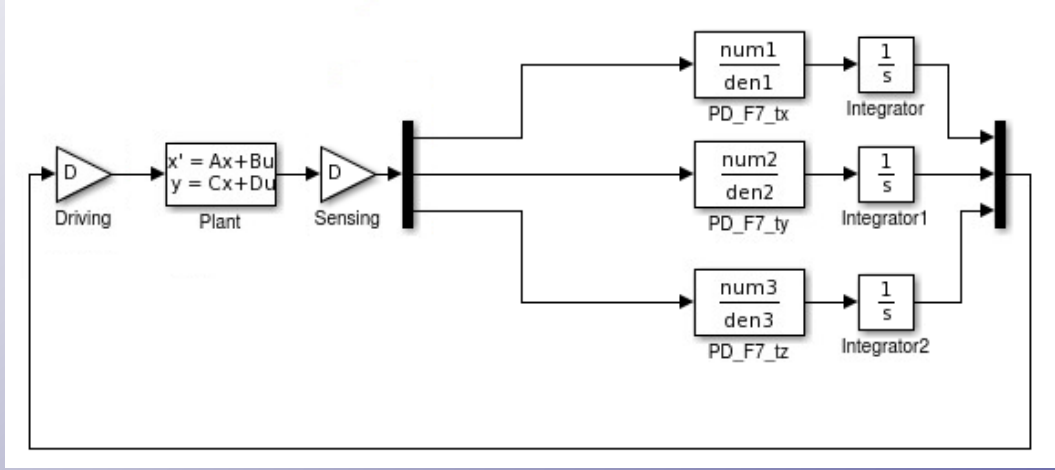
F7 Control

3 PID Filters are now used for the F7 control of all long suspensions.

F7 Control (tx, ty, tz)

6 x 6 plant matrix:
6 LVDTs x 6 Coils on the F7

3 x 3 Diagonalized Control Matrix



- Tx and Tz filters are required to damp a 400 mHz payload mode.

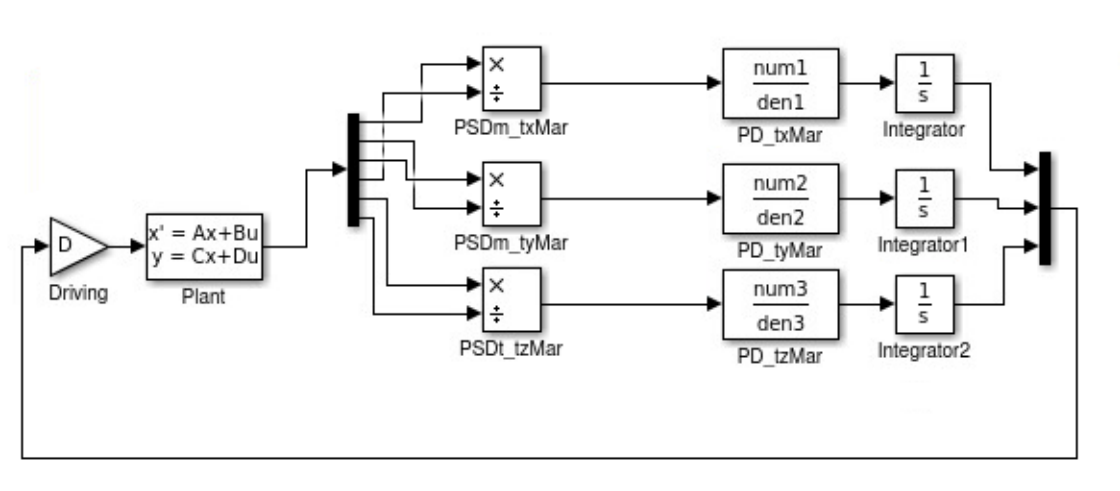
Local Control

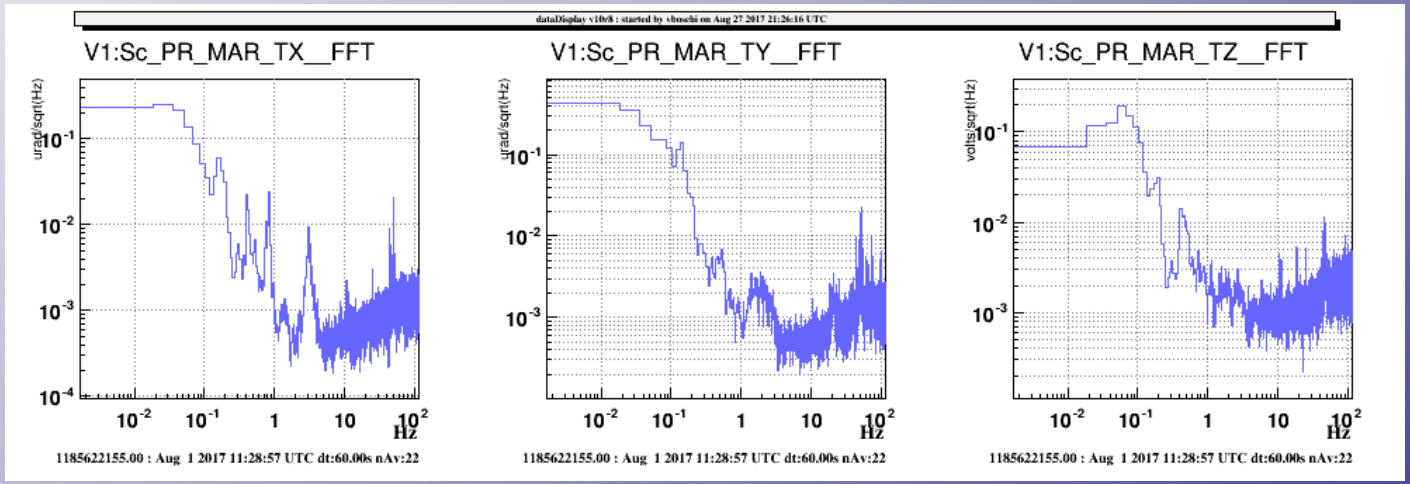
Local Control (tx, ty, tz)

3 x 8 plant matrix:
3 PSD signals x 8 Coils on Marionette

3 x 3 Diagonalized Control Matrix

Bang-bang control (Coarse)
PID (Fine)



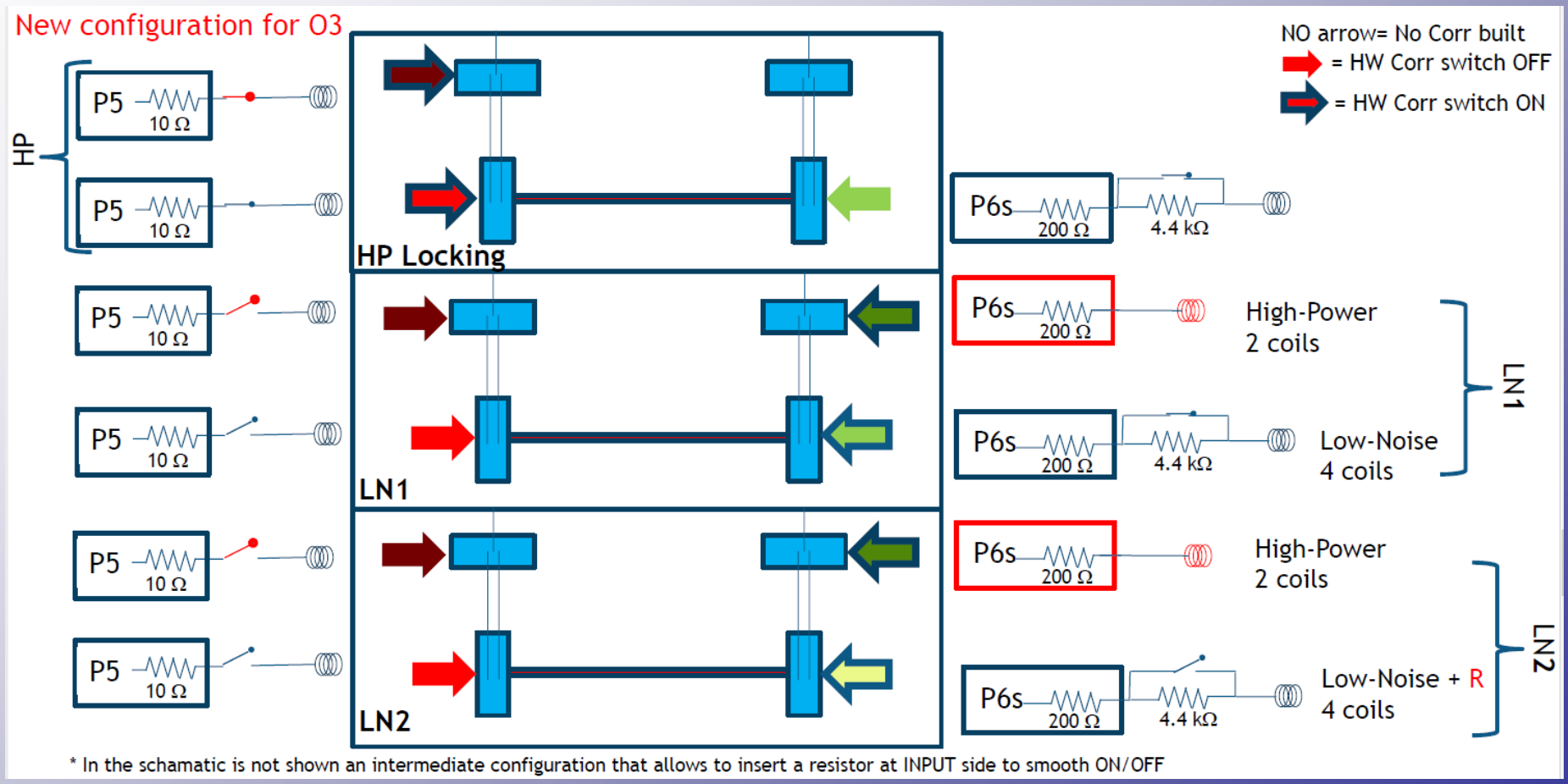


A few nrad/sqrt(Hz) of spectral diplacement above 1 Hz

Locking

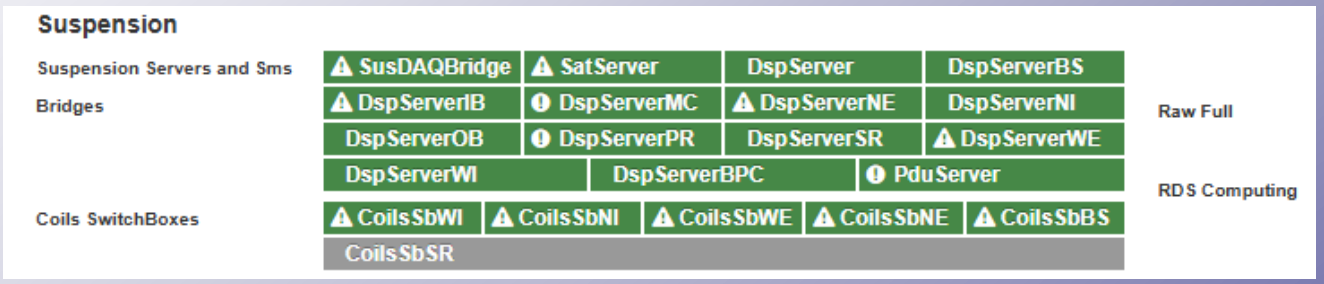
Three mirror actuation modes are used:

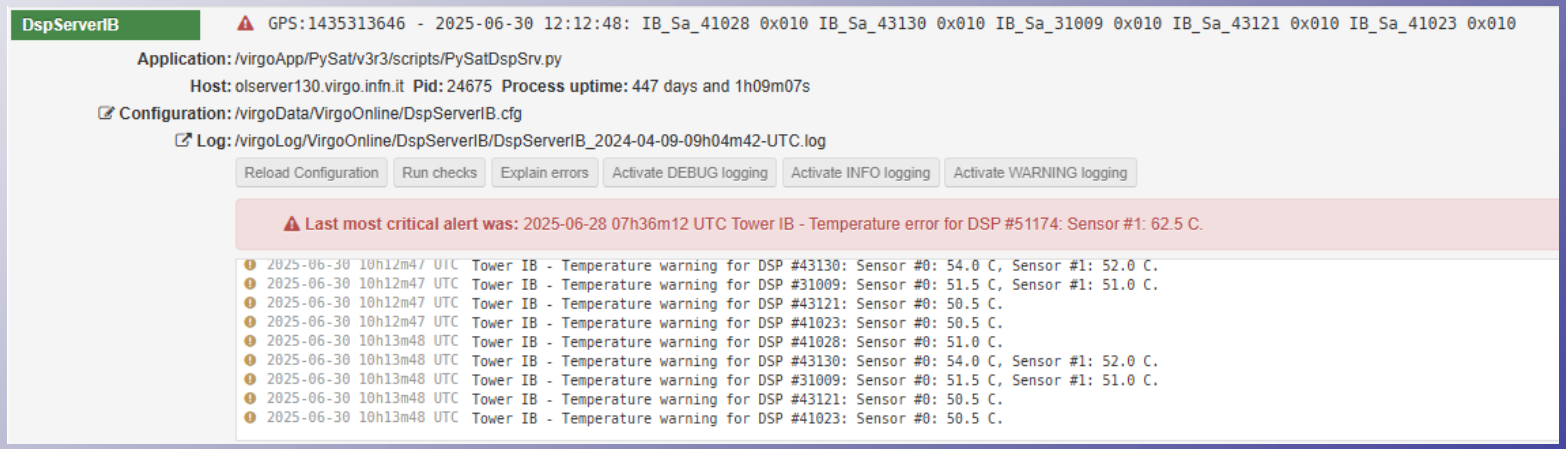
- High power (10 Ohm output resistance) for lock acquisition only
- Low Noise 1 (200 Ohm output resistance + 1st order shaping filter)
- Low Noise 2 (4.6 kOhm output resistance + 1st order shaping filter)



Supervisor

- Supervisor is an important part of the subsystem since it allows to monitor the status of both and hardware and software and to interact with the DSP from external code such as Python.
- SAT Supervising software used in O2 and O3 was based on TANGO. However, it was extremely complex to maintain and unstable.
- The supervisor has been fully re-written by Akis with more functionality, less complexity and more stability.





Thank you for your attention!!