Real-time Monitoring of Virgo Super-Attenuators

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25th IEEE Real Time Conference - La Biodola, Elba, Italy

Summary

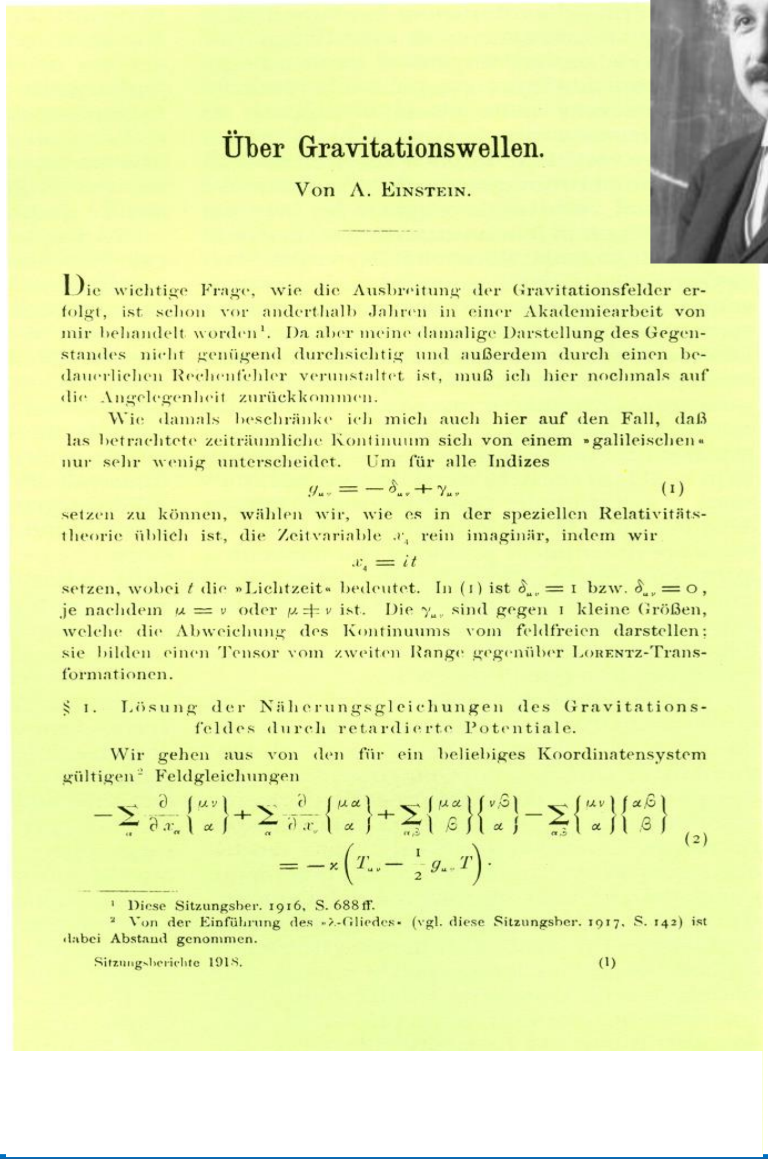
- VIRGO Gravitational Waves Detector
  - Gravitational Waves
  - Detector
- Seismic Isolation
  - Super Attenuator
- Control System
  - System in use
  - Running upgrade
  - Future upgrades

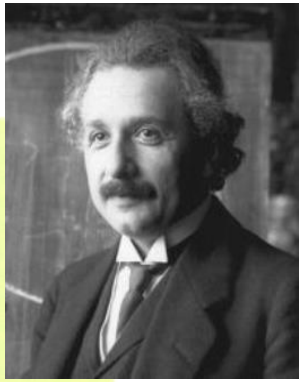

VIRGO
https://www.ego-gw.it/
IEEE MILESTONE
Gravitational-Wave Antenna, 1972-1989
Initially developed from 1972 to 1989, the Gravitational-Wave Antenna enabled detection of ripples in spacetime propagating at the speed of light, as predicted by Albert Einstein's 1916 Theory of General Relativity. Construction of the Virgo Gravitational-Wave Observatory commenced in 1997. In 2017, Virgo and two antennas located in the U.S.A. launched the era of Multi-Messenger Astronomy with the coordinated detection of gravitational waves from a binary neutron star merger.
February 2021
IEEE

Gravitational Waves

Einstein describes gravity as a property of space-time that is deformed by masses.

Acceleration of large masses on the 'fabric' of space-time produce tiny ripples, Gravitational Waves, that propagates at the speed of light alternately stretching and squeezing the fabric.





Über Gravitationswellen.

Von A. Einstein.

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß las betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

setzen zu können, wählen wir, wie es in der speziellen Relativitätstheorie üblich ist, die Zeitvariable x_4 rein imaginär, indem wir

$$x_4 = it$$

setzen, wobei t die »Lichtzeit« bedeutet. In (1) ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$ ist. Die $\gamma_{\mu\nu}$ sind gegen 1 kleine Größen, welche die Abweichung des Kontinuums vom feldfreien darstellen; sie bilden einen Tensor vom zweiten Range gegenüber Lorentz-Transformationen.

§ 1. Lösung der Näherungsgleichungen des Gravitationsfeldes durch retardierte Potentiale.

Wir gehen aus von den für ein beliebiges Koordinatensystem gültigen[2] Feldgleichungen

$$-\sum_{\alpha} \frac{\partial}{\partial x_\alpha} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} + \sum_{\alpha} \frac{\partial}{\partial x_\nu} \begin{Bmatrix} \mu\alpha \\ \alpha \end{Bmatrix} + \sum_{\alpha\beta} \begin{Bmatrix} \mu\alpha \\ \beta \end{Bmatrix} \begin{Bmatrix} \nu\beta \\ \alpha \end{Bmatrix} - \sum_{\alpha\beta} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} \begin{Bmatrix} \alpha\beta \\ \beta \end{Bmatrix} = -\varkappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right). \qquad (2)$$

[1] Diese Sitzungsber. 1916, S. 688 ff.

[2] Von der Einführung des »λ-Gliedes« (vgl. diese Sitzungsber. 1917, S. 142) ist dabei Abstand genommen.

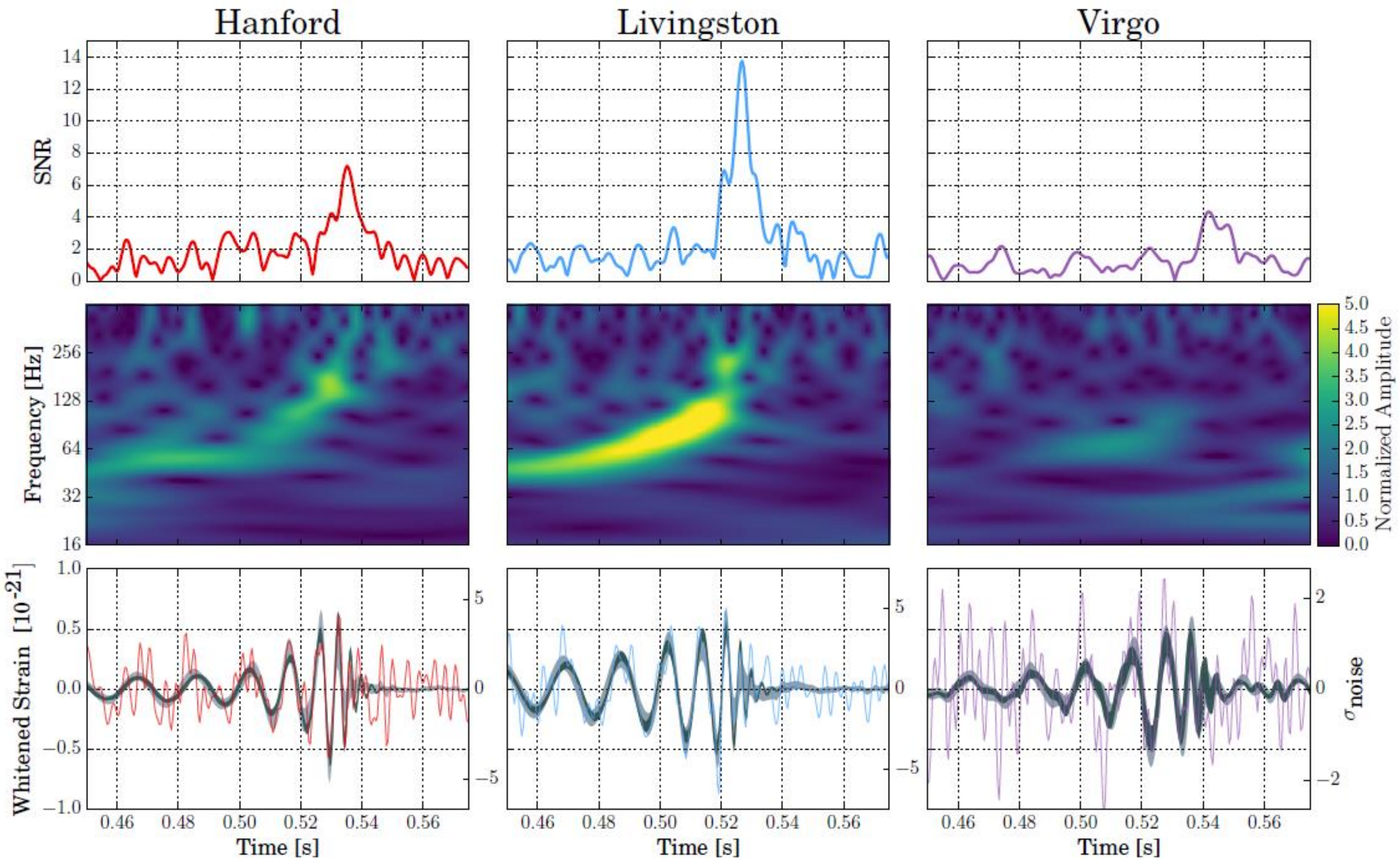
Sitzungsberichte 1918. (1)

Gravitational Waves (II)

- How Small?
- To detect a gravitational wave, we must measure displacements in the order of 10^{-18} m over a length of 3 km
- Such displacement is so small that it is extremely difficult to figure out what does it mean. To give some hint, it is like:
  - Detecting a variation in the order of one atom diameter in the Earth-Sun distance.
  - Detecting a variation in the order of one human hair in the distance of Proxima Centauri (about 4 ly).
  - Detecting the variation in the oceans level pouring in a glass of water.

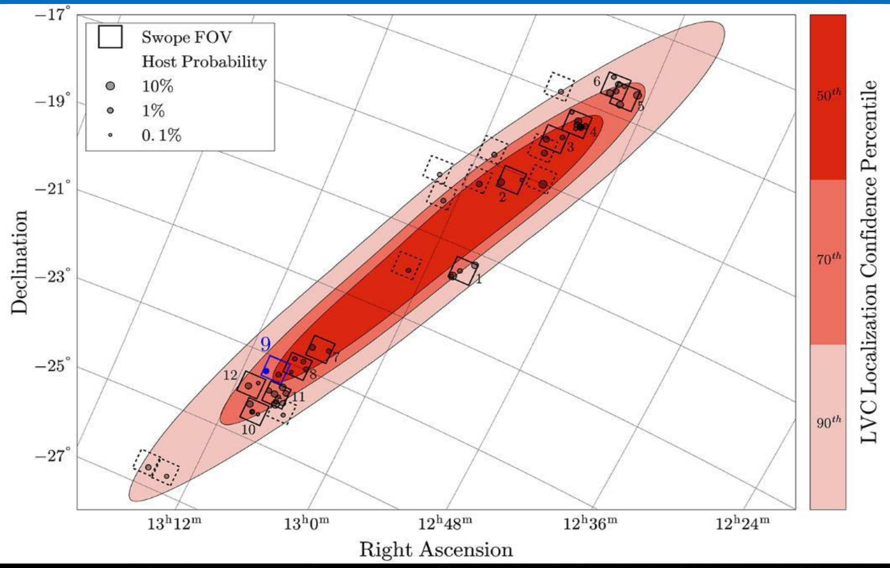
GW170814: 3 Detectors

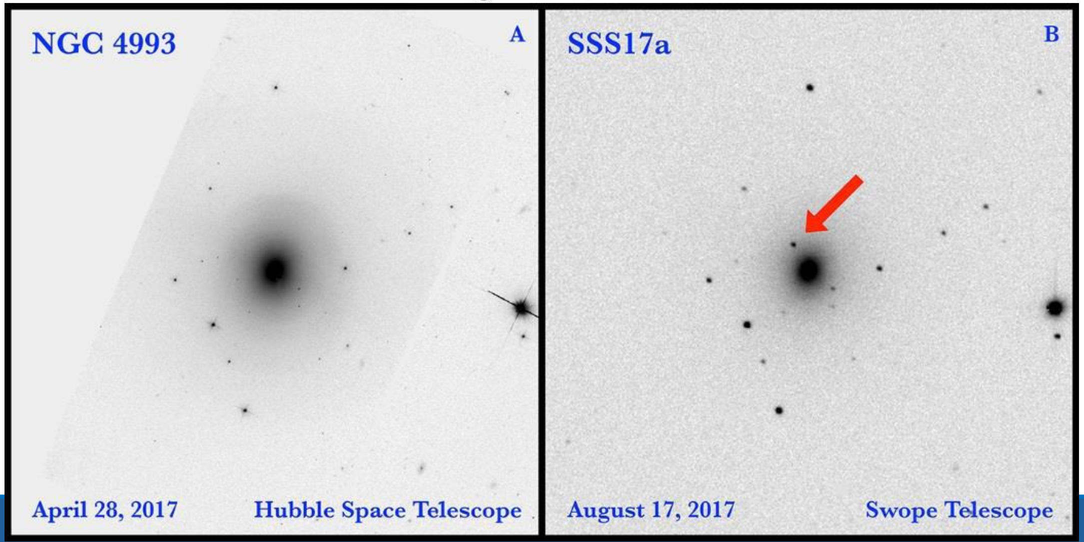
LIGO Scientific Collaboration



Dawn of multi-messanger era

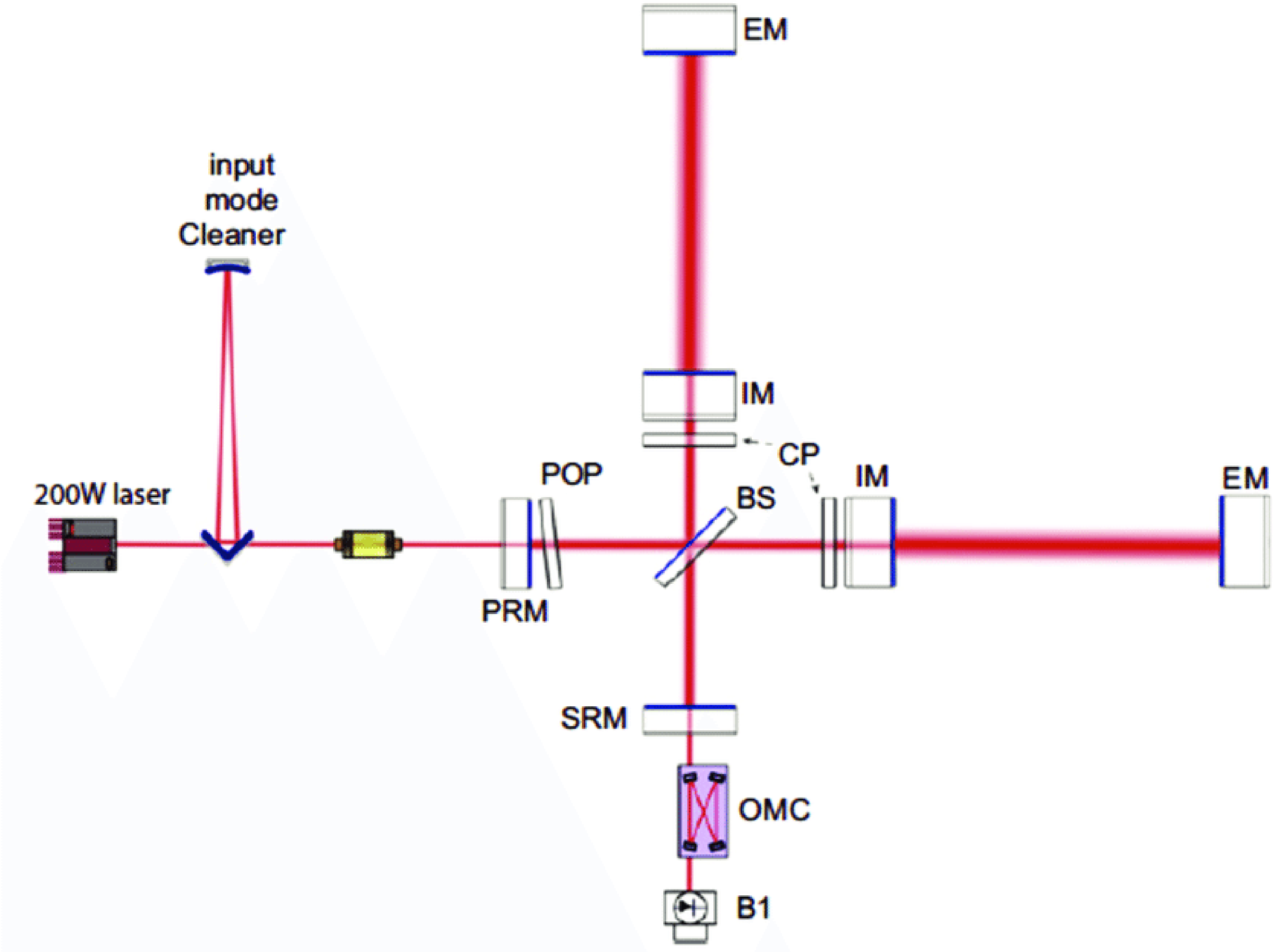
- Astronomical Observatories were triggered with the coordinates of the event
- Starting from search area and using the additional information about event distance, astronomers could select a small set of galaxies to look at
- About 80 observatories all over the world followed the birth a new star, a kilonova at ~130–140 million light-years from us

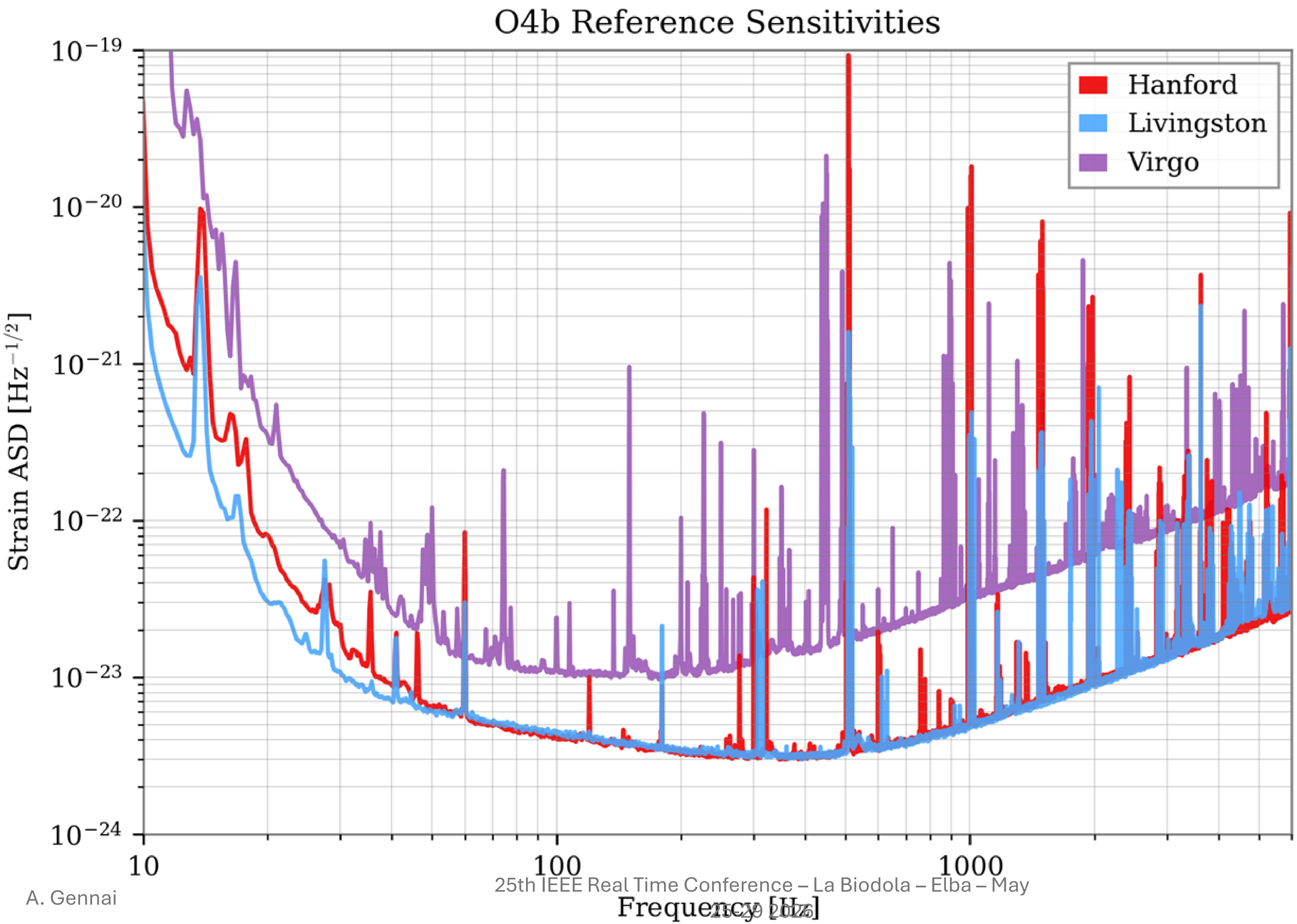




Optical Layout

- VIRGO interferometer is more complex than basic Michelson.
- The two arms are Fabry Perot cavities 3km long
- Makes use of Power Recycling technique to increase the total circulating power
- Signal Recycling

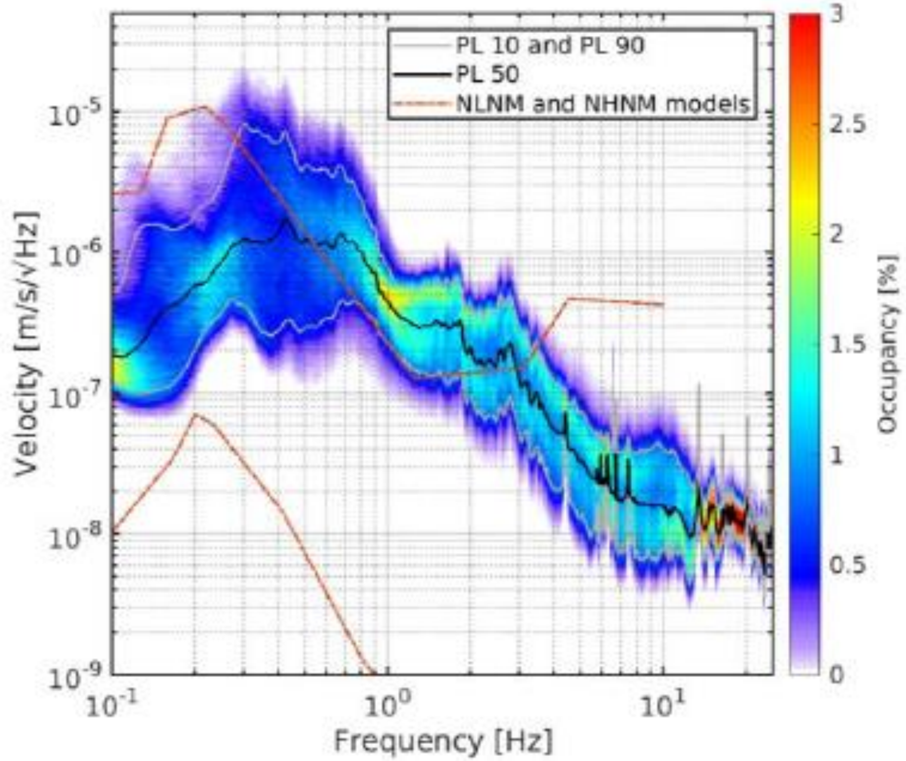




Source:
LIGO-T2500390-v1
Francesco Di Renzo

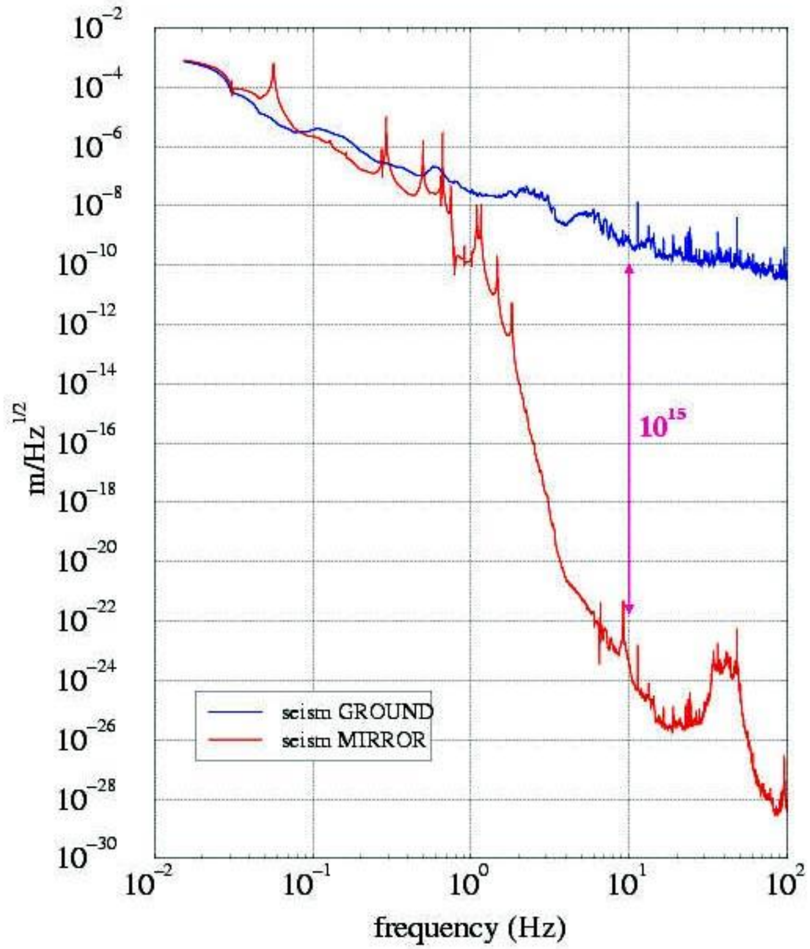
Seismic Noise

- Different sources:
  - Tidal strain (about 200 µm peak-to-peak between input and end mirrors)
  - Earthquakes
  - Seismic noise
    - Microseism: dominant between 0.1 and 1 Hz mainly due to sea waves
    - Anthopogenic:
      - between 1 and 5-10 Hz, due to heavy vehicles traveling along near roads and bridges
      - Between 10 and 40 Hz, due to onsite ‘traffic’.



Seismic Noise Reduction

- Seismic noise limits sensitivity of ground-based detectors at low frequencies - “seismic wall”
- Typical seismic noise at Virgo site at 10 Hz is ~ few x 10^{-10} m/√Hz
  - many orders of magnitude above target noise level
- Solution: isolation system with a multistage pendulum: the **Super-Attenuator**
- Isolation required in vertical direction as well as horizontal due to cross-coupling



Super-Attenuator

INFN PISA

ELSEVIER

Physics Letters A

Volume 124, Issues 4–5, 28 September 1987, Pages 253-257

Three-dimensional seismic super-attenuator for low frequency gravitational wave detection

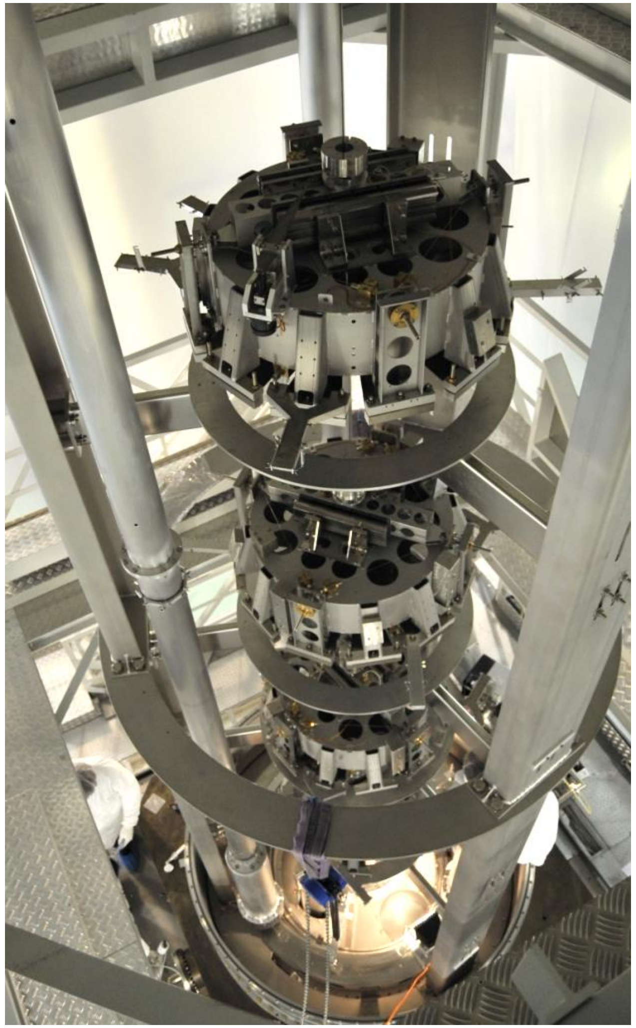
R. Del Fabbro [3], A. Di Virgilio [3], A. Giazotto [3], H. Kautzky [1 3], V. Montelatici [2 3], D. Passuello [3]

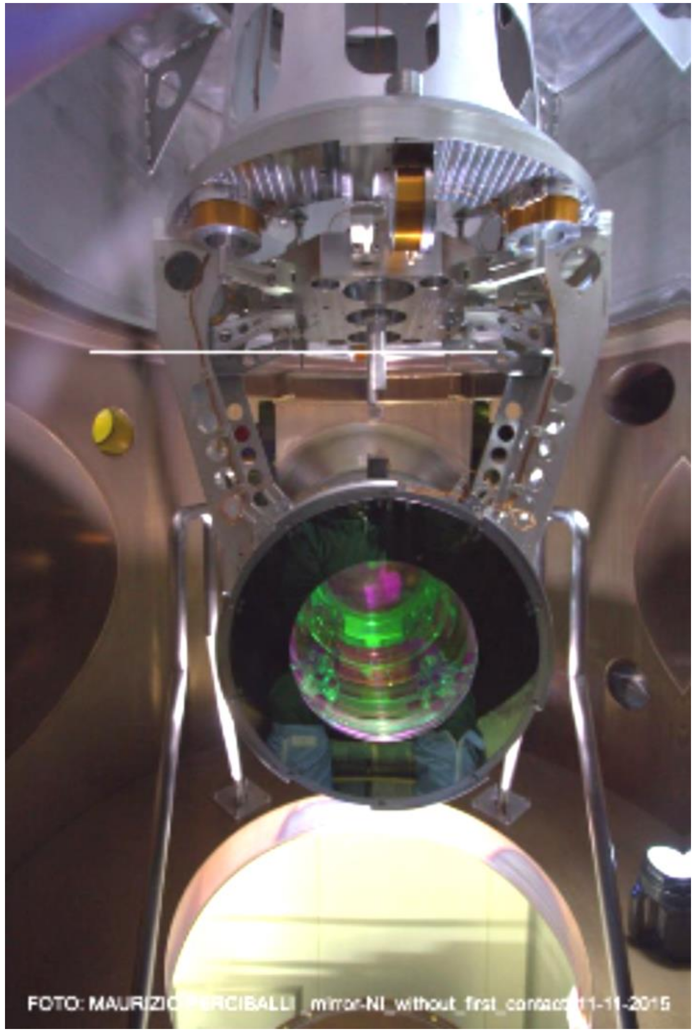
INFN Sezione di Pisa and Dipartimento di Fisica, Università di Pisa, Pisa, Italy

Received 26 June 1987, Accepted 27 July 1987, Available online 19 September 2002.

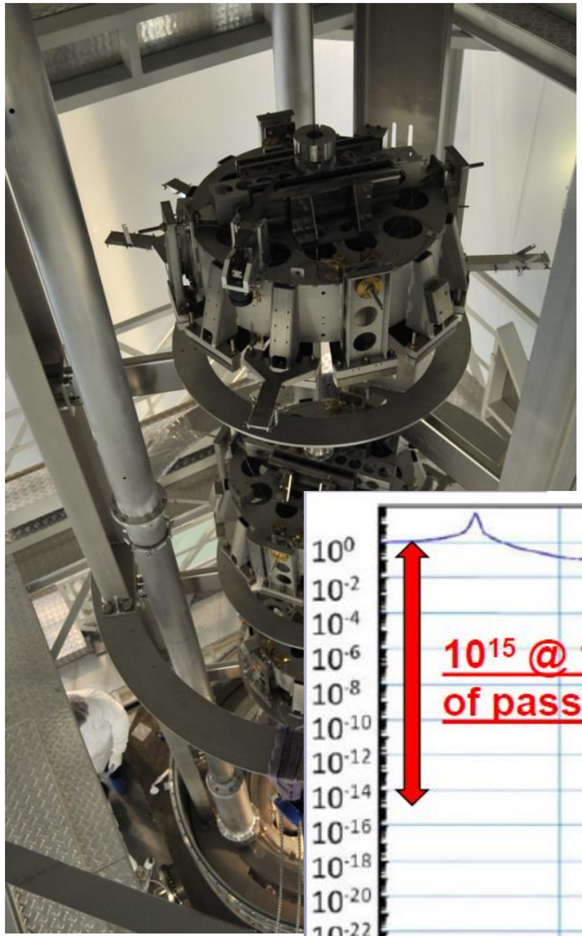
Seismic Filters

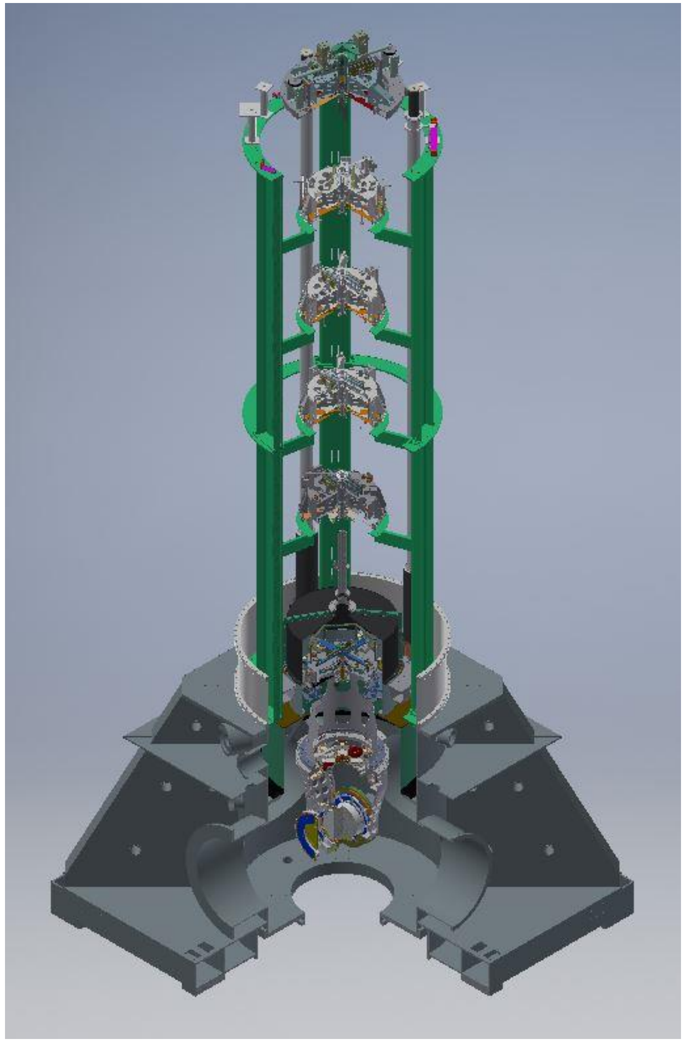
- The Super-Attenuator is a chain of mechanical stages acting as filters for seismic noise
- At the end of the chain of filters there is the Payload: Marionette and Mirror





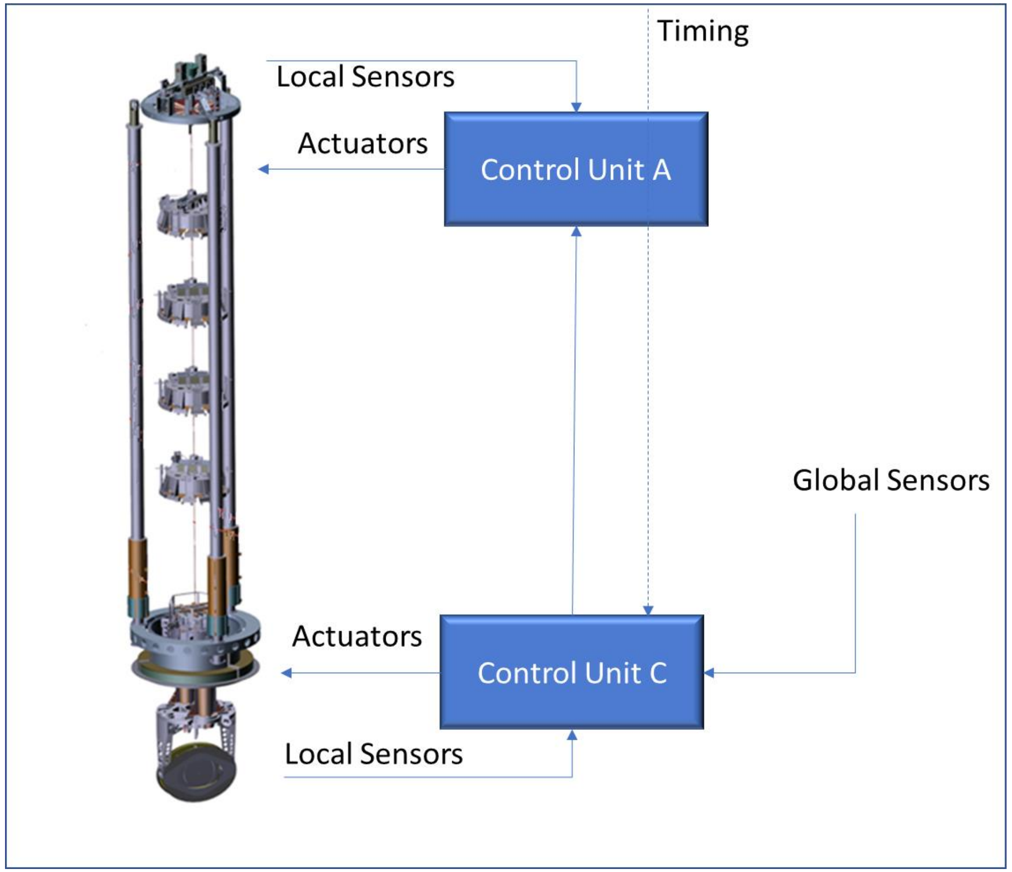
Super-Attenuator



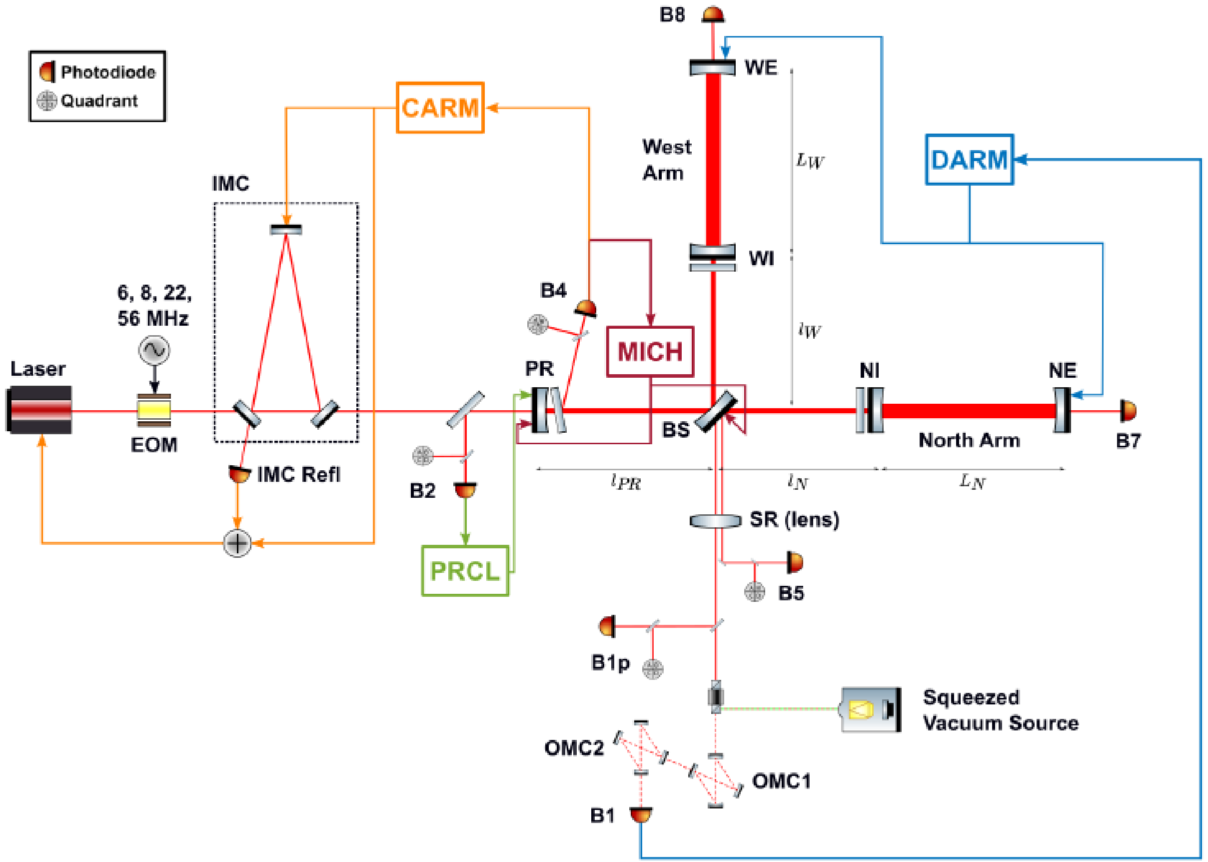


Virgo Control

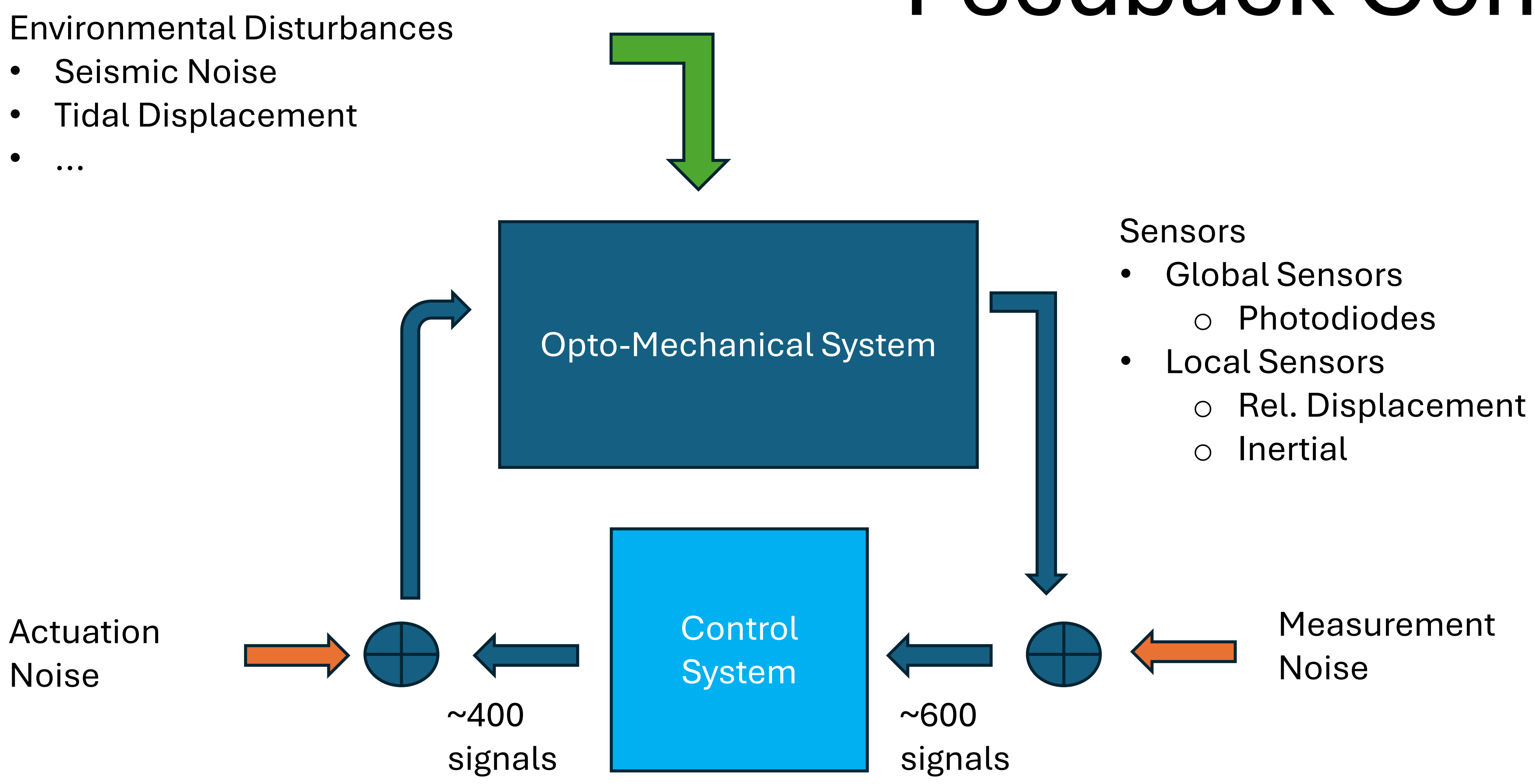
- Seismic Isolation System



- Interferometer

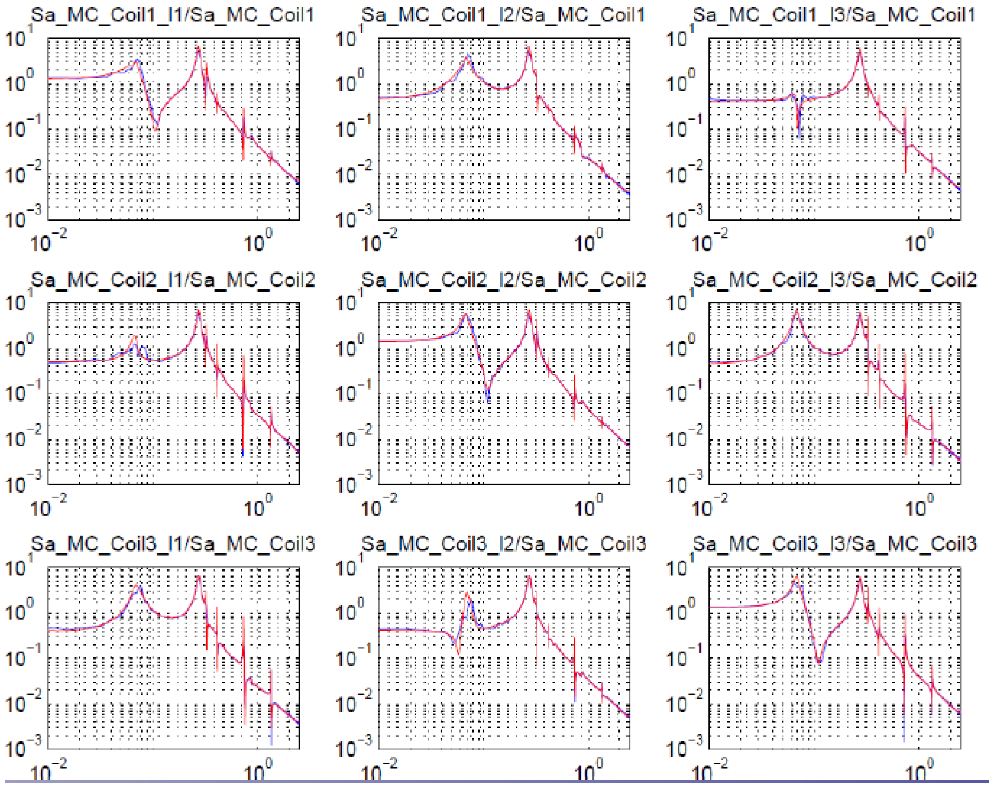


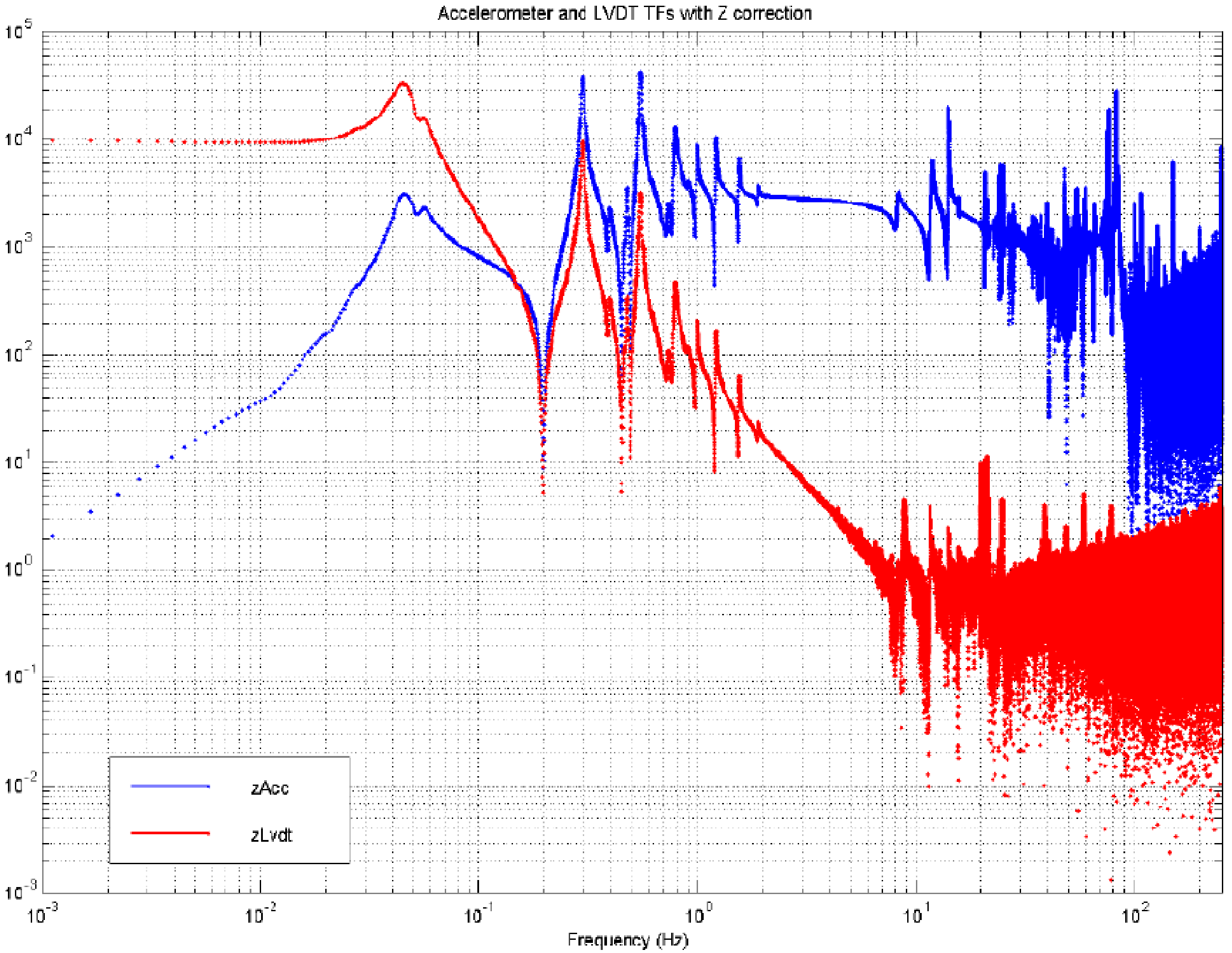
Feedback Control



Mechanical transfer functions between force applied on Super-Attenuator top stage.

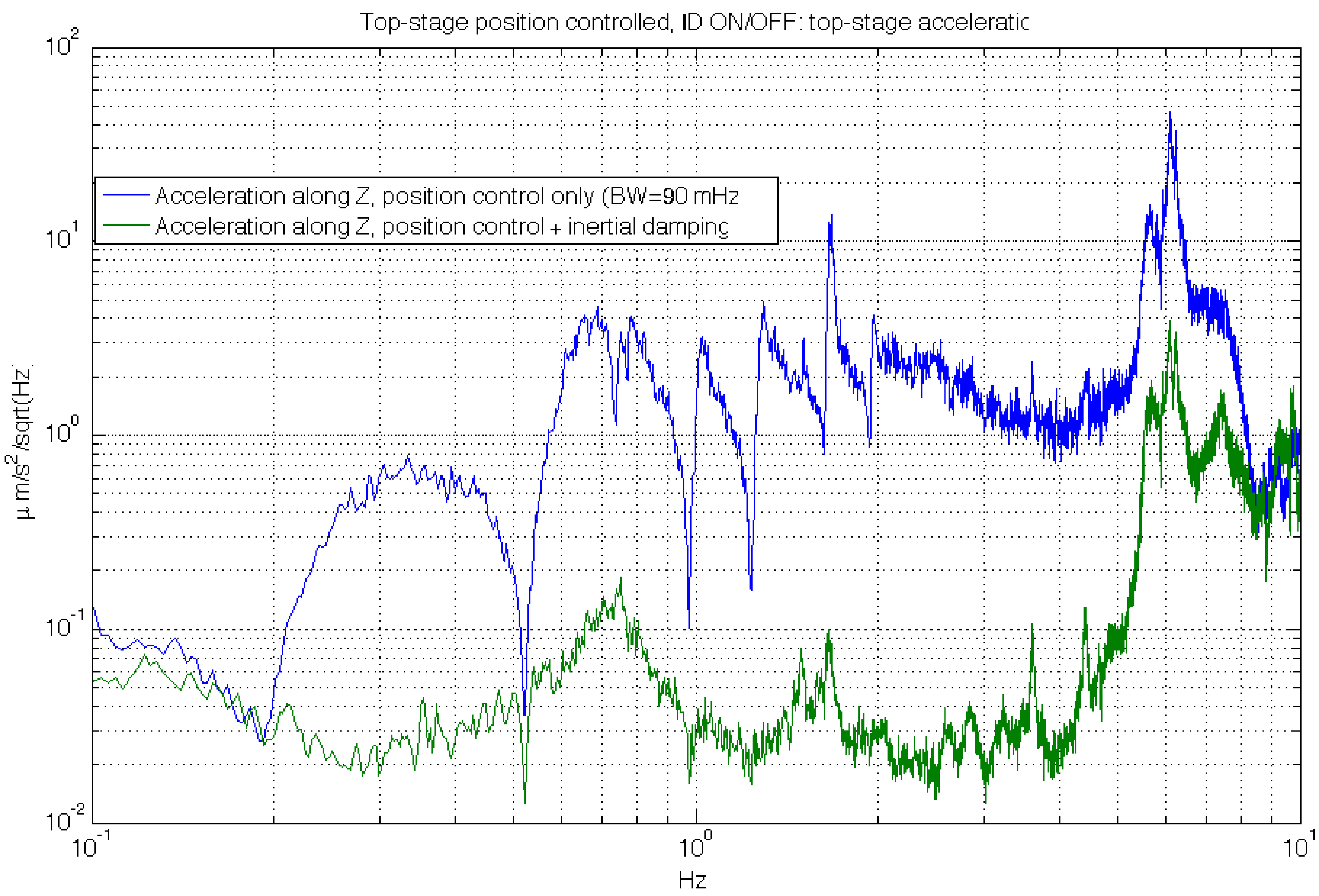
High complexity and high dynamics



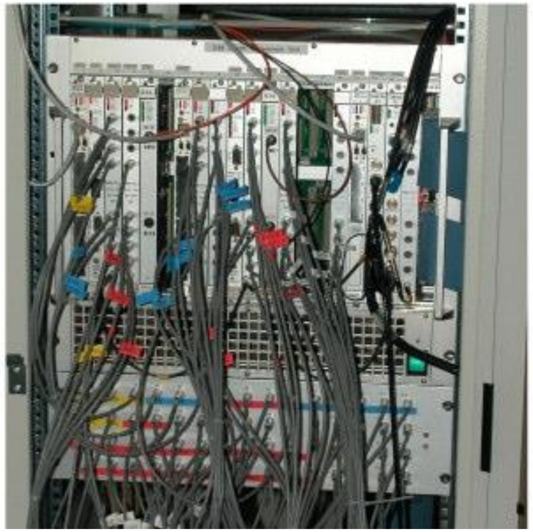


Open loop (blue) vs closed loop (green) top stage acceleration spectra

Without local control of the normal modes of the Super-Attenuator, residual motion of suspended mirrors would be too large

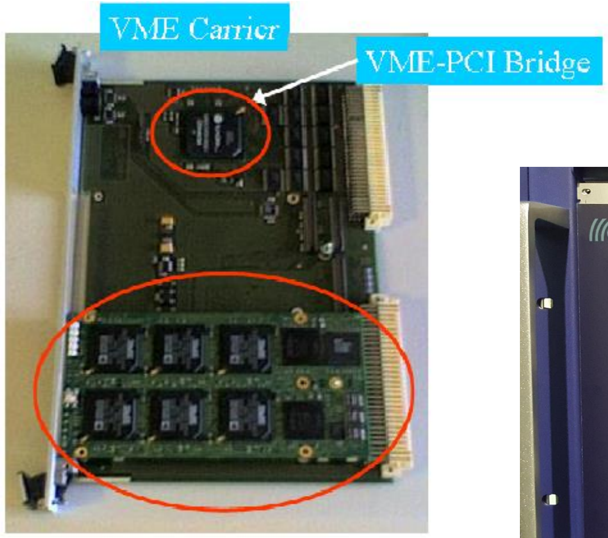


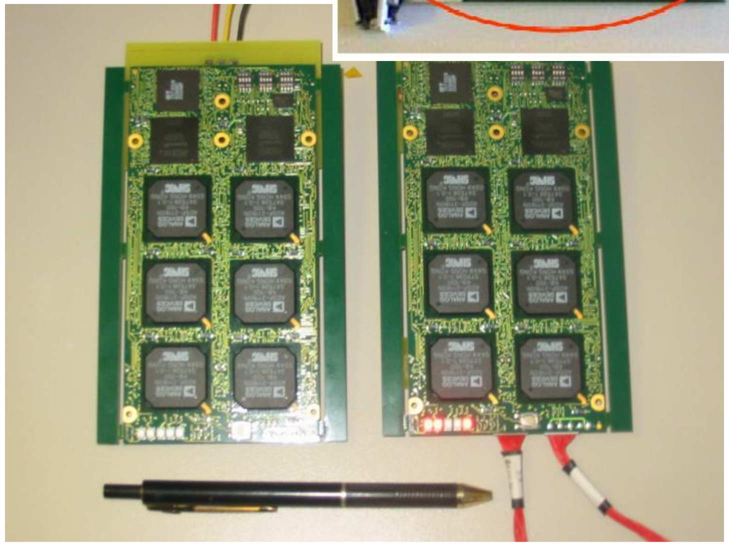
Control Hardware Evolution
10 Super Attenuators: 20 Local Control Units

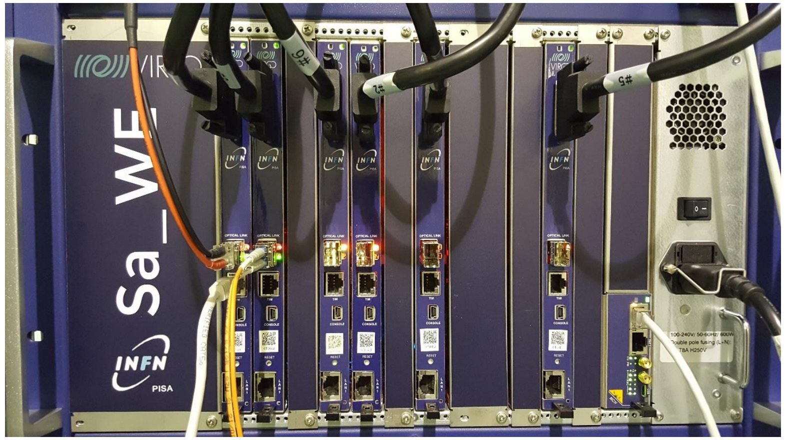


1999-2009: VME Crate (10 Units)
2x Motorola DSP96002
2x PowerPC
60x Analog IO (16bit ADC – 20bit DAC)
NIM Crate for FE Electronics

2009-2014: VME Crate
2x Multi ADSP21160
2x PowerPC
60x Analog IO
NIM Cratefor FE Electronics



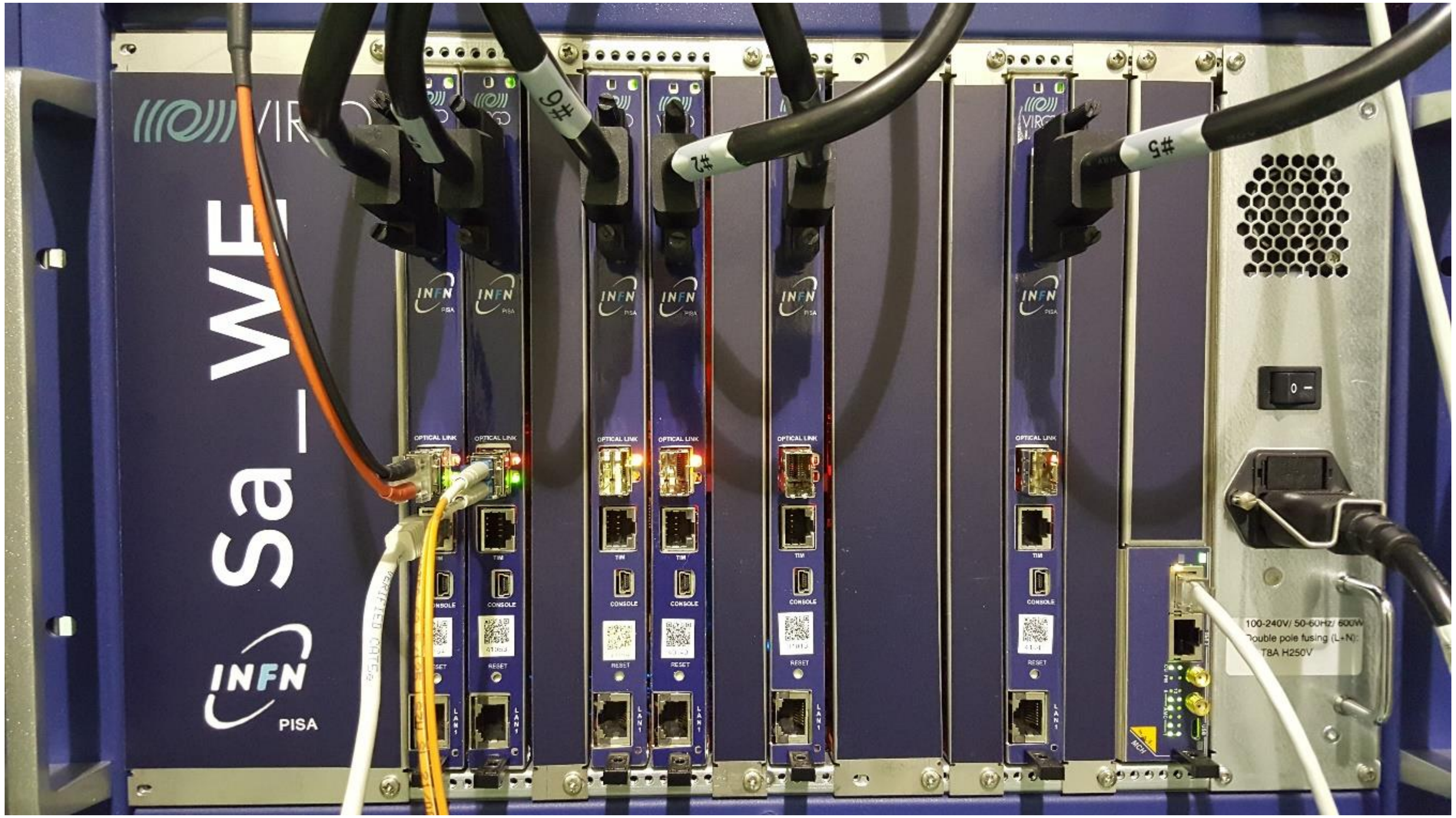




2015-2026: MTCA Crate (20 units)
Up to 12x TMS320C6678 DSPs
Up to 72x Analog IO including FE electronics

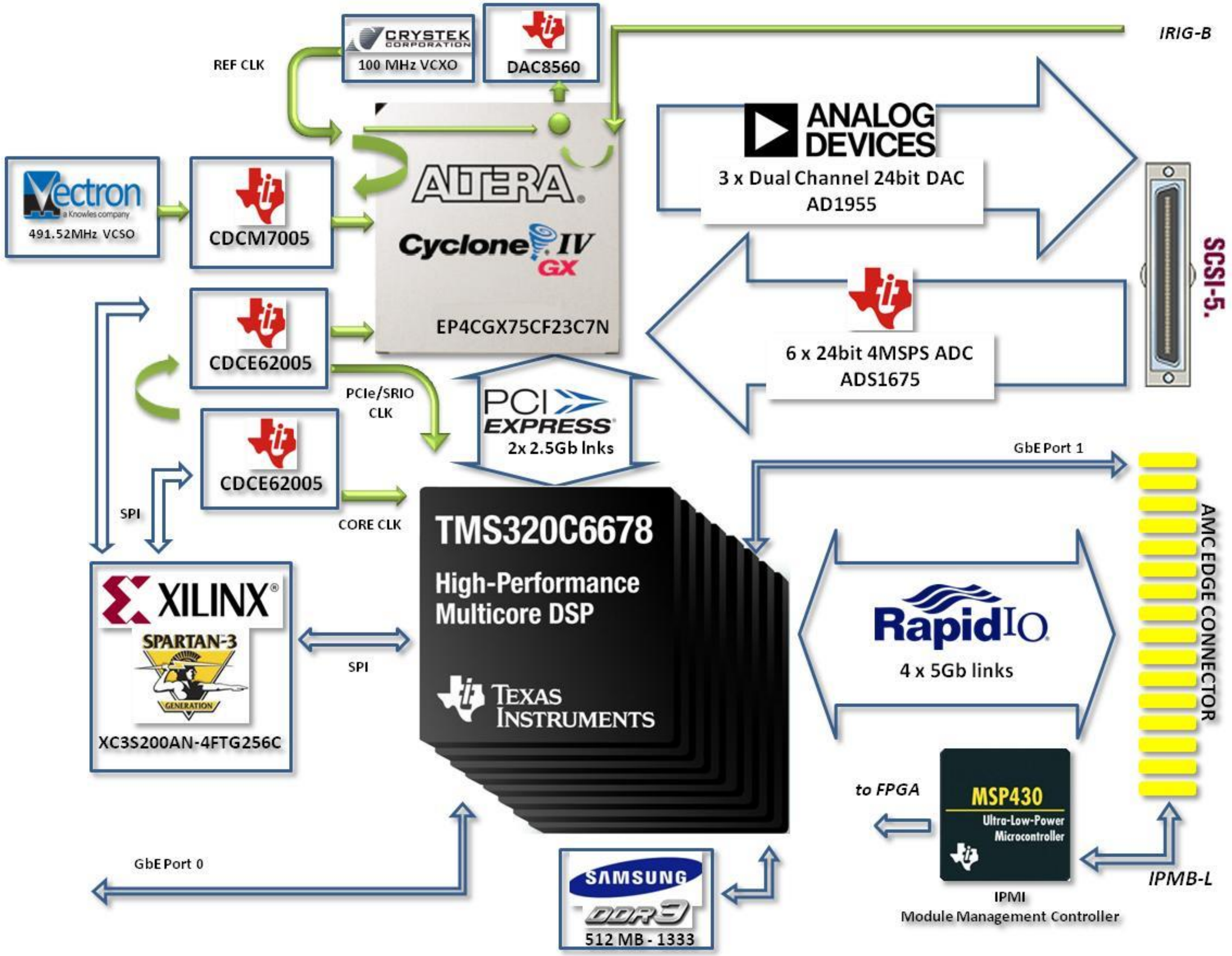
Local Control Unit

- MicroTCA (customized)
- 20 Control Units
- 130 UDSPT boards
- Each board equipped with:
- 6ch ADC (24bit, 3.84MSPS)
- 6ch DAC (24bit 320 kSPS)
- 8 core DSP TMS3206678
- Analog electronics
- Up to 60 GFLOPS per board

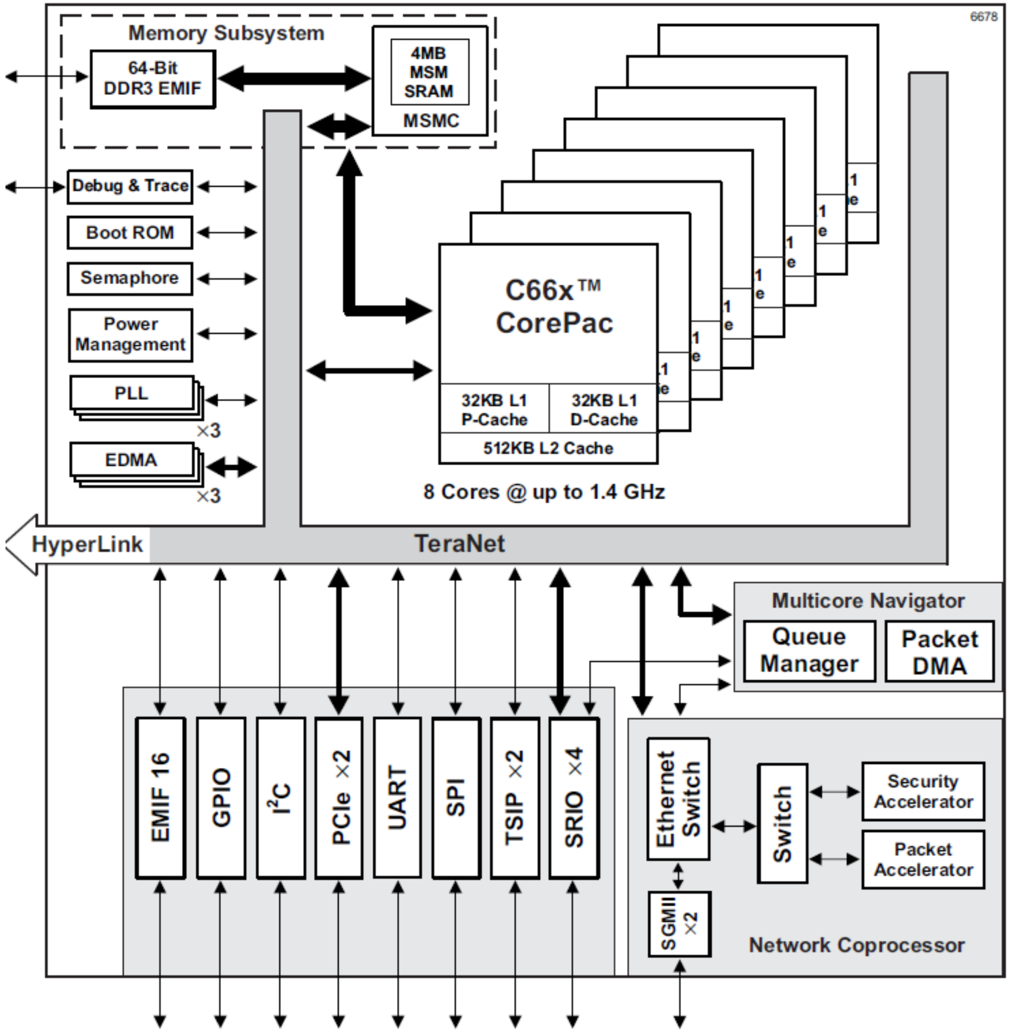


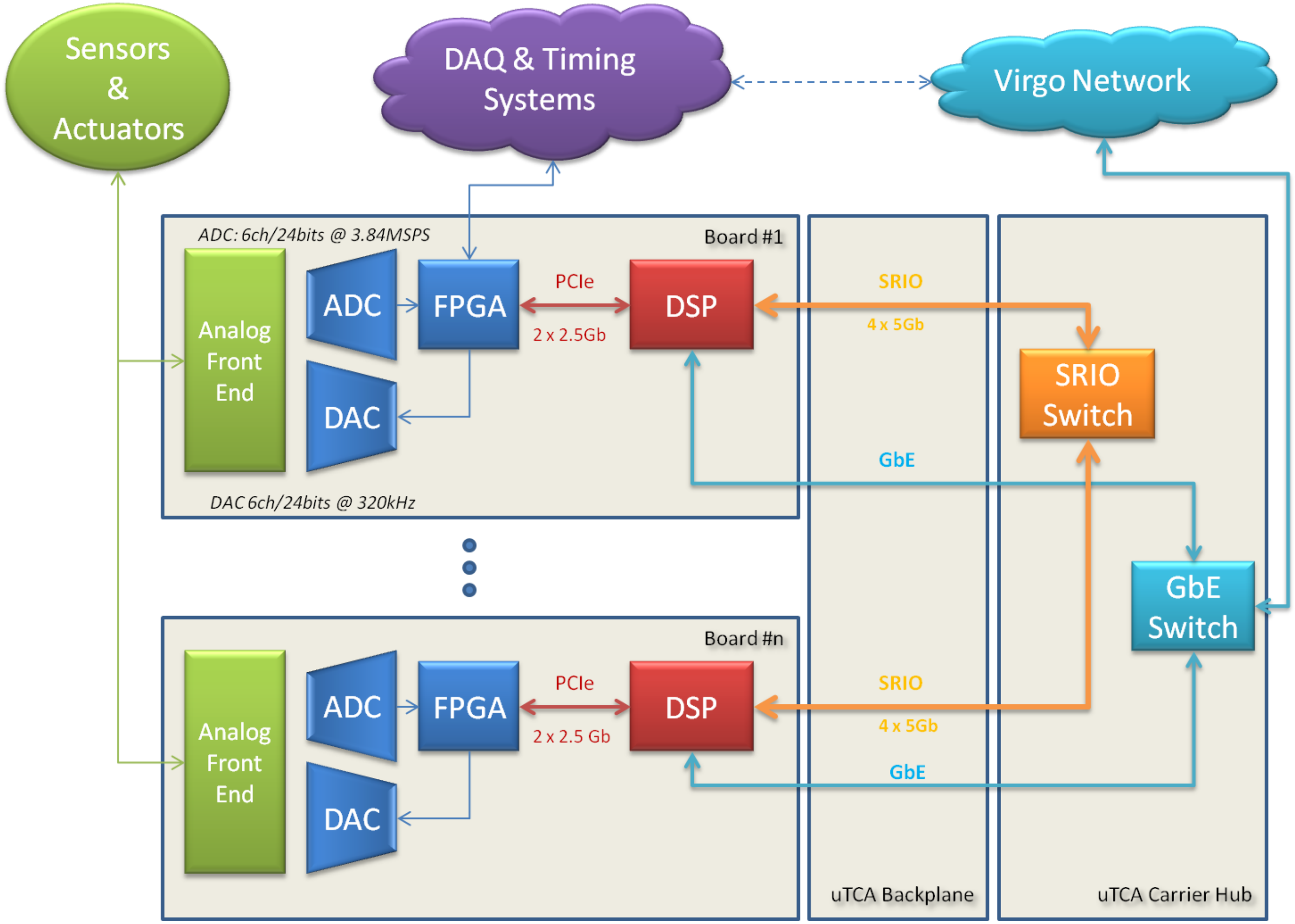
UDSPT Module

- Customized (taller) MicroTCA
- DSP <-> AD/DA PCIe
- DSP <-> DSP SRIO



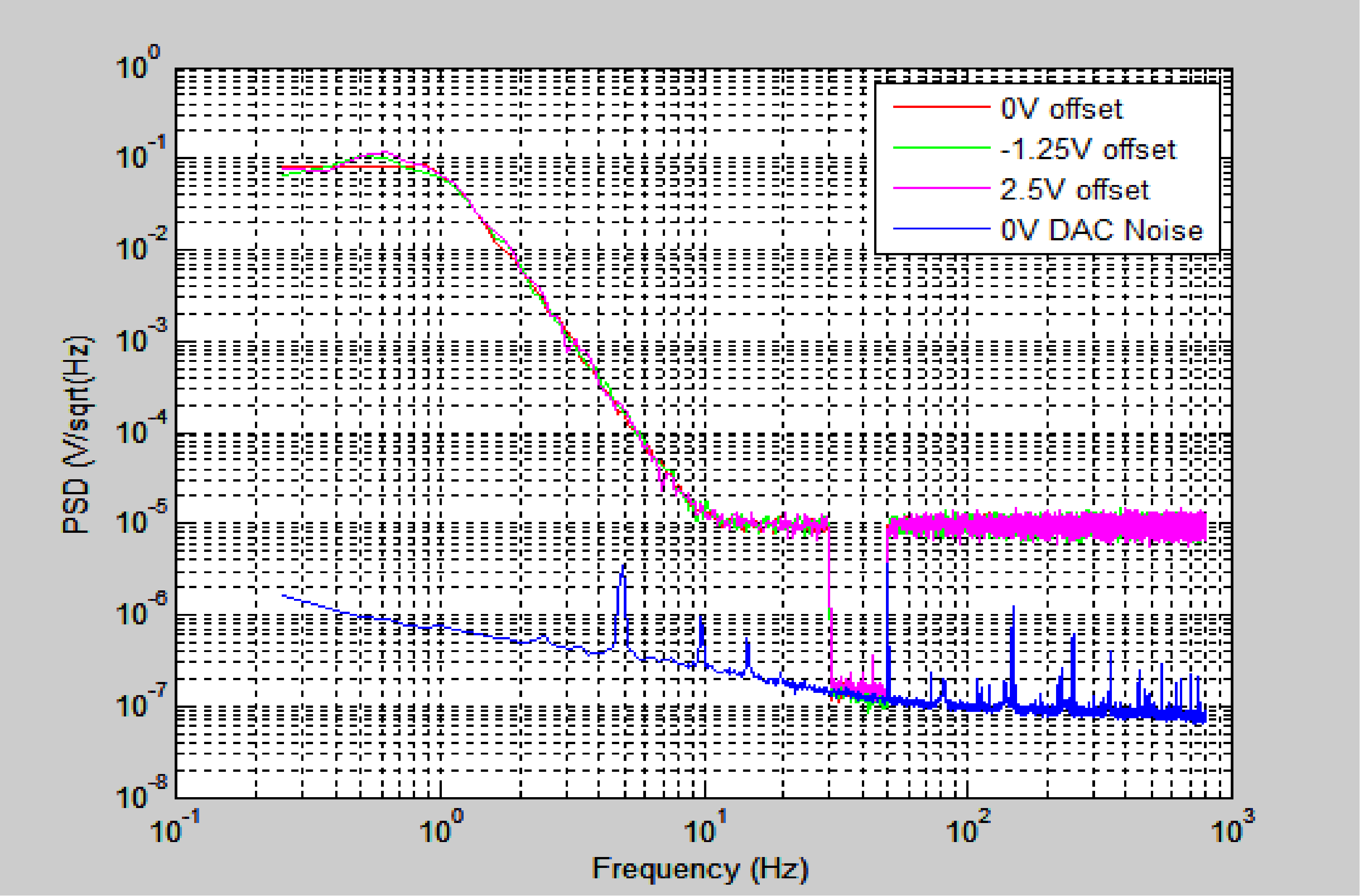
Interconnections





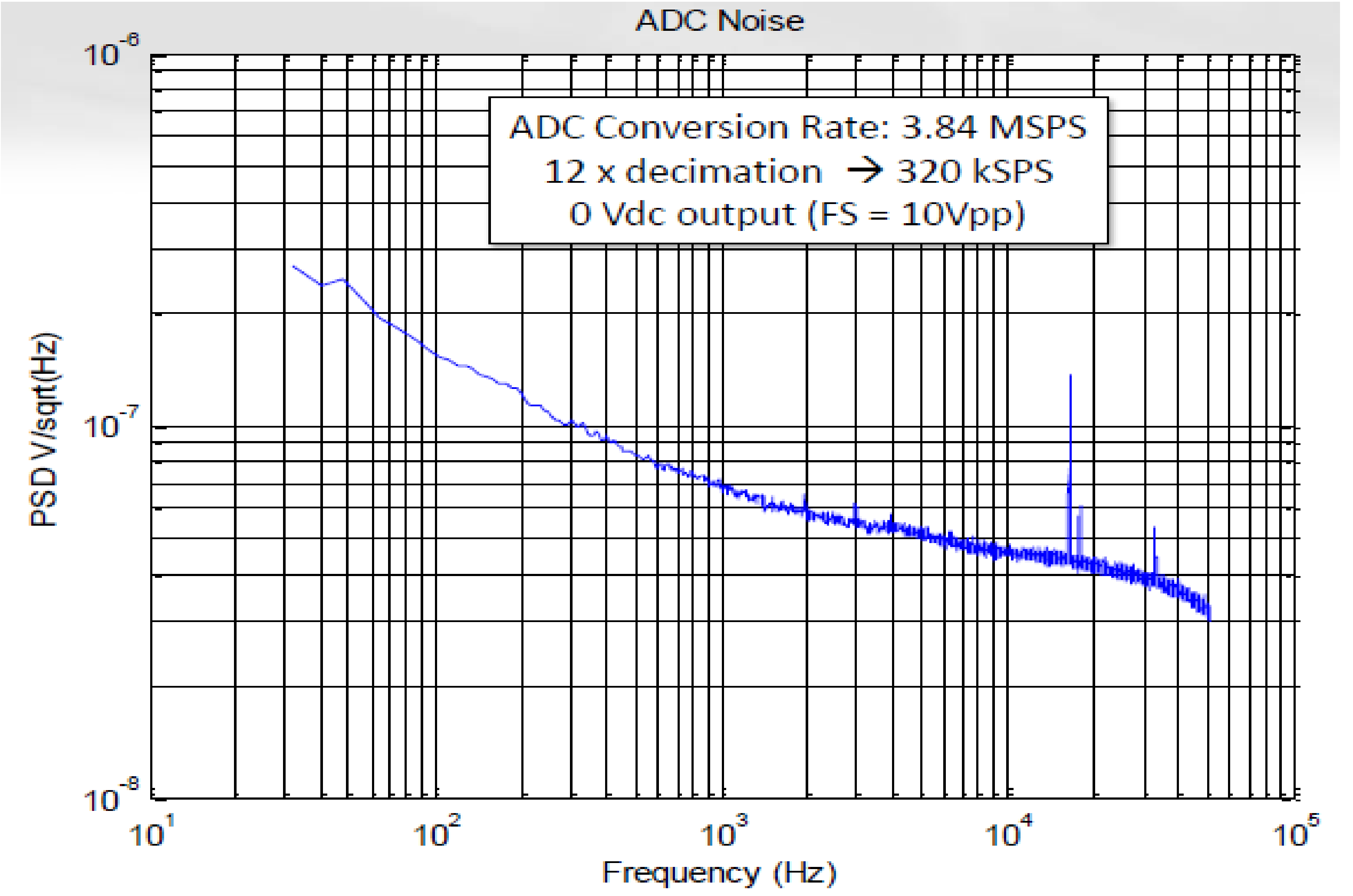
Digital To Analog Converters

- AD1955 stereo digital audio converter 24bit operated at 320kSPS
- Benchmark for linearity check (no up-conversion of low frequency components)
- Due to high dynamics of mechanical systems, we need double precision



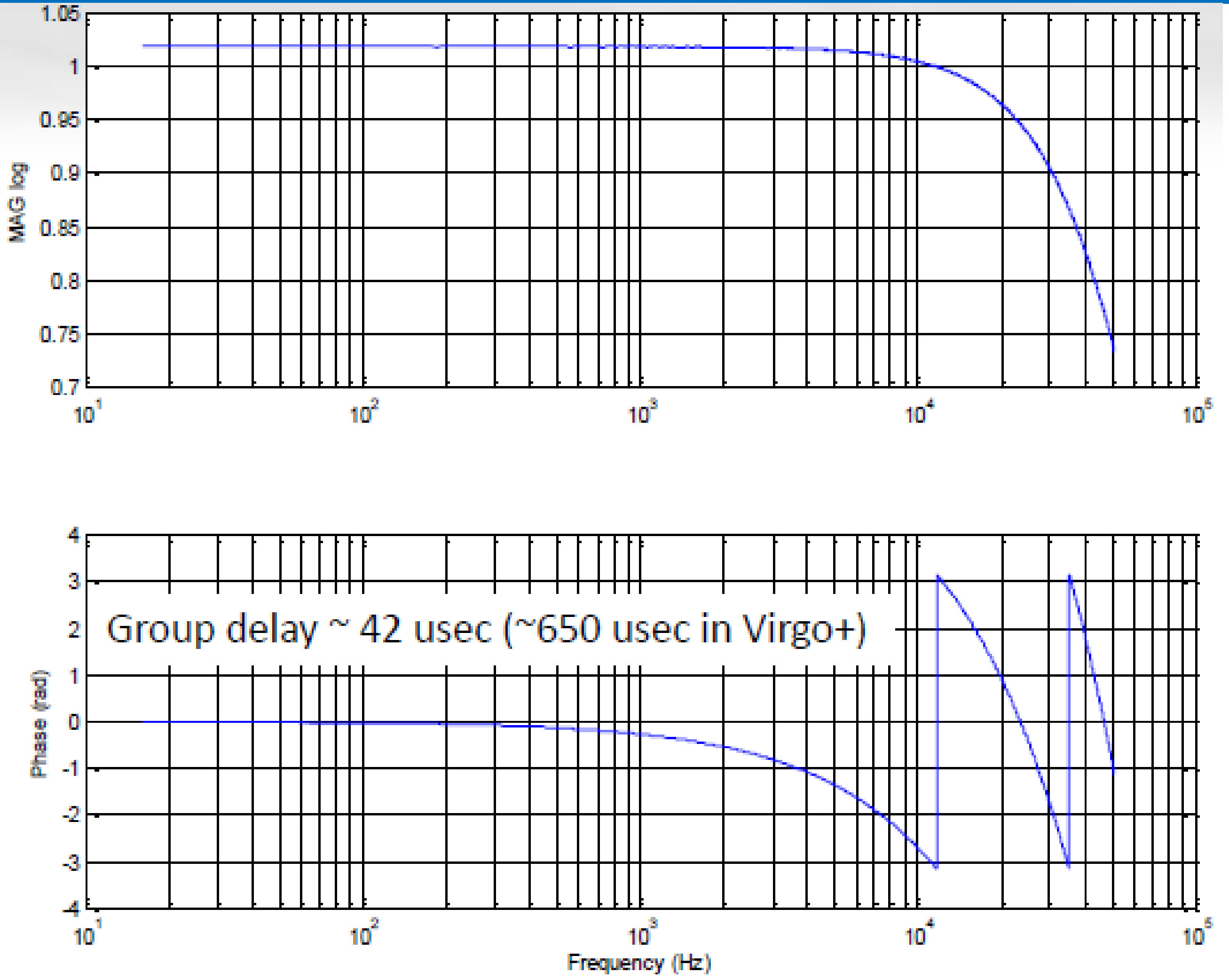
Analog to Digital Converters

- TI ADS1675, delta-sigma converter, 24bit 4MSPS
- Local sensors that monitor the Super Attenuator movements are typically inductive (ironless LVDT) operating at 50 kHz

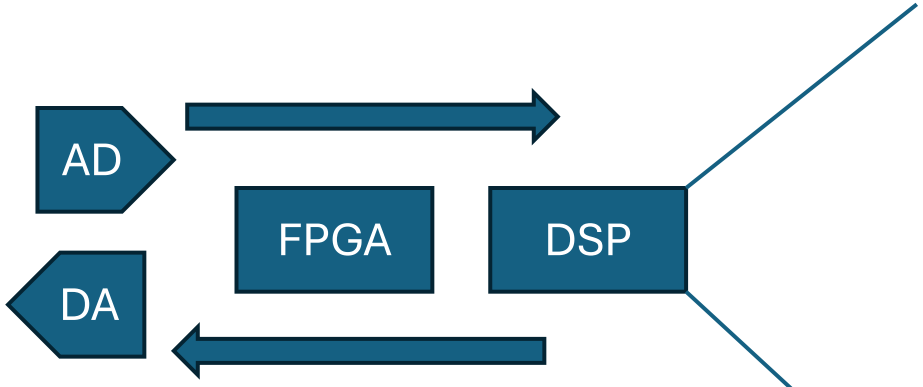


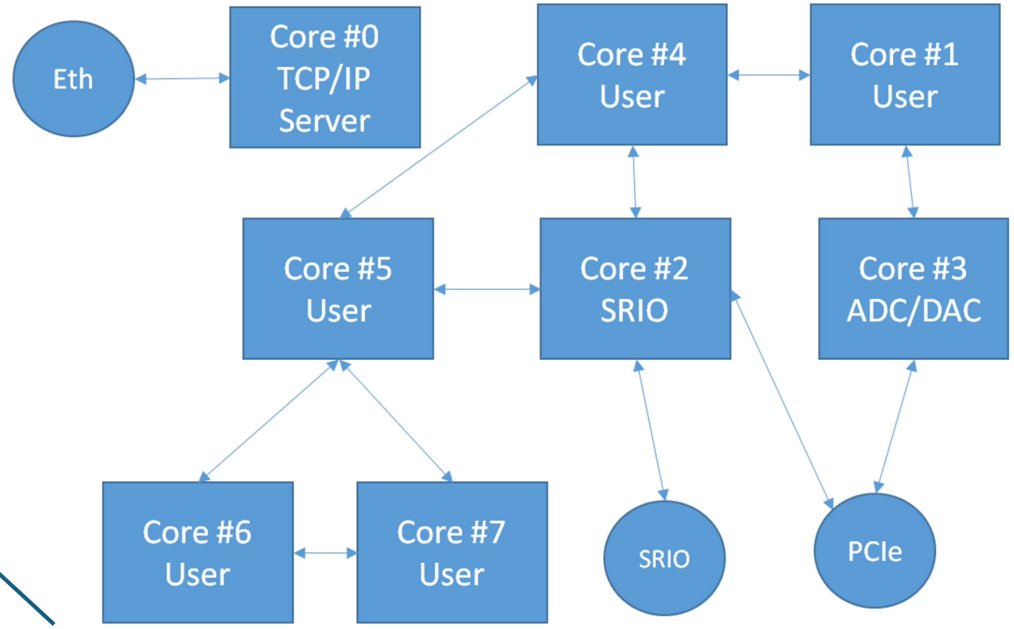
AD → Processing → DA

- Since we are dealing with feedback loops, delay must be kept low.
- The minimum delay we can achieve is 42 us
- 50 us delay produce a 18deg phase shift at 1 kHz, therefore limiting the unity gain frequencies in the kHz range.



Data Fluxes

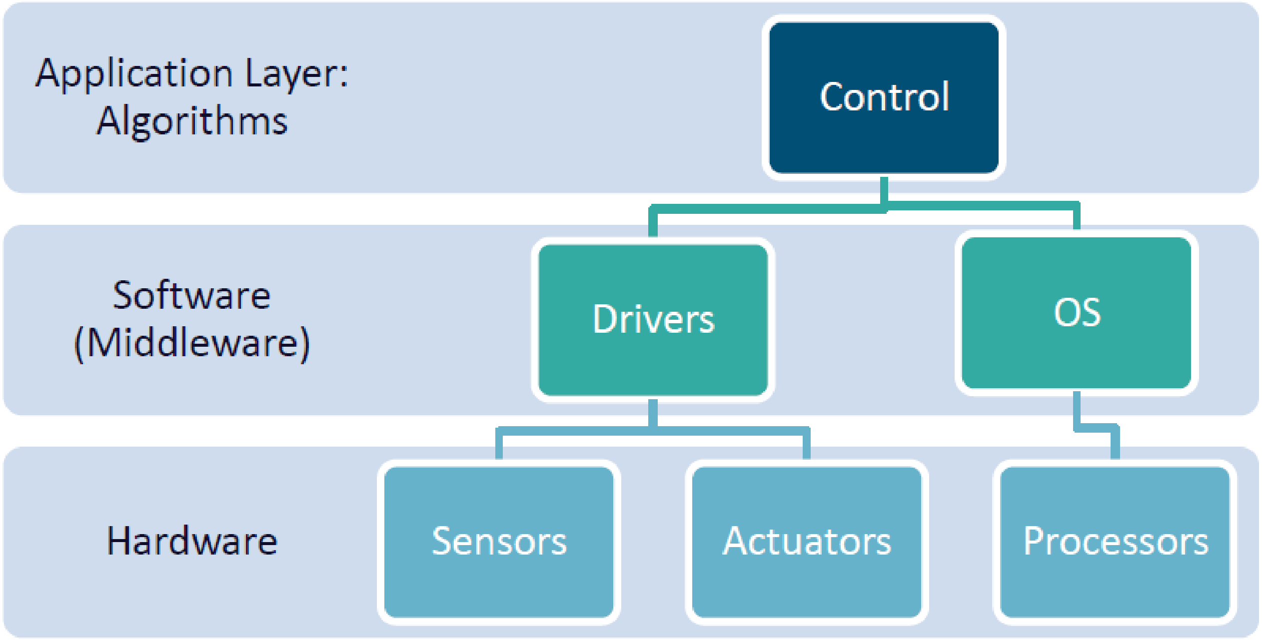




- 10 Super-Attenuators, 20 LCU, ~130 boards
- ~600 input channels 24b 3.84MSPS
- ~600 output channels 24b 320kSPS
- All conversions are synchronous triggered by the Virgo timing system

Software Architecture

- Users act only on application layer
- The hard real-time part of user's code run on two parallel task whose activation frequency is selectable between 10 and 320 kHz. Compiler checks if there are timing issues
- Native programming language using a library of optimized functions



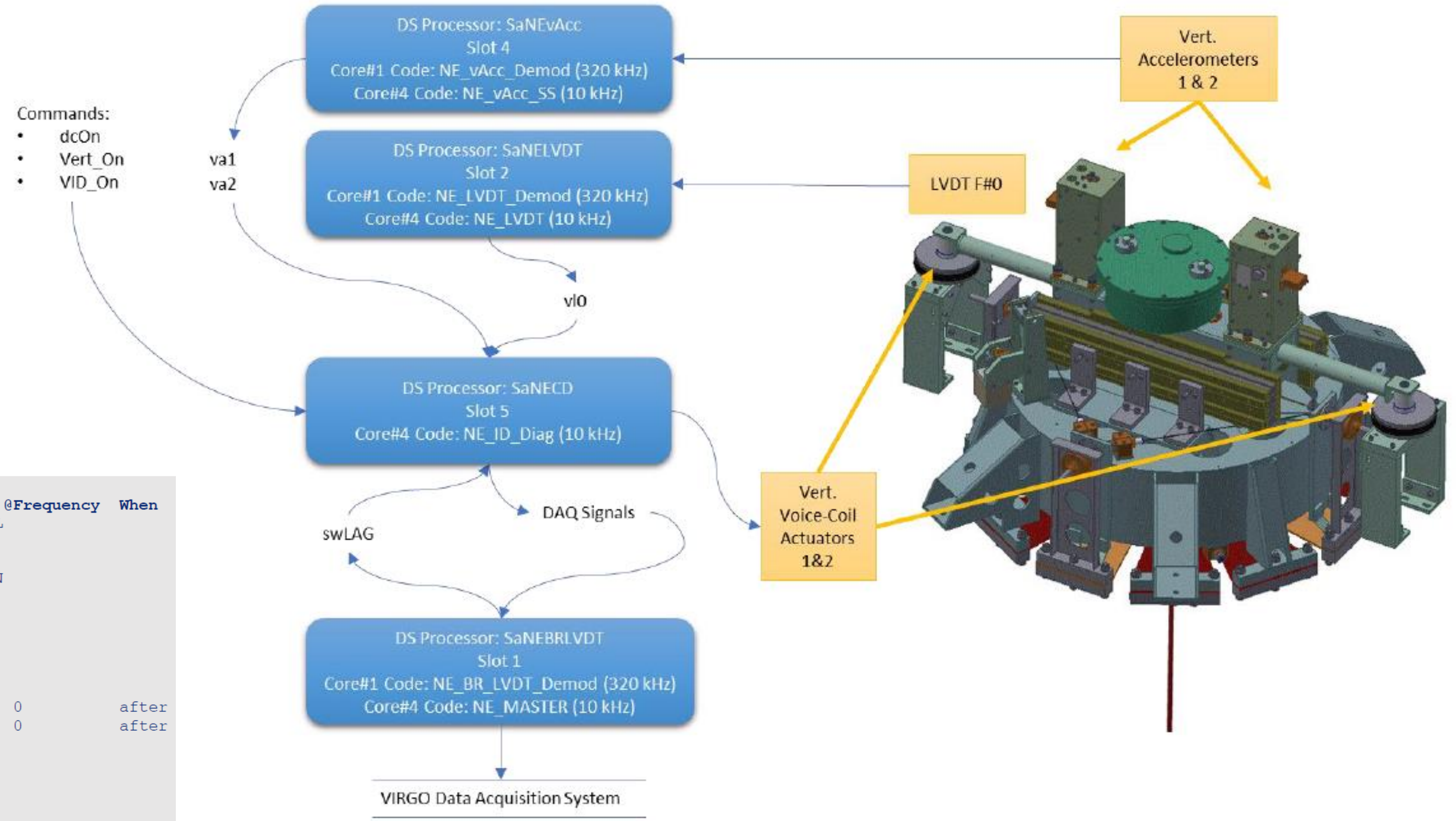
Example: ScNE LCU Tasks List

- 9 user tasks are running. Activation frequency is 40 kHz for all of them except for the last one activated 320’000 times per second. Execution is parallel: each tusk runs on a dedicated DSP core.
- 24 system task are running simultaneously to user tasks (ADC decimation, DAC inputs interpolation, Data Acquisition signals pre-processing, communication, ...)

Task Name	Activation Period (us)	Exec Time (us)	Digital IO	MFLOPS
NE_LN.hrd	25	3.2	56	43
NE_Mar_LN.hrd	25	5.2	50	64
NE_PSDf.hrd	25	3.7	167	119
NE_PSDi.hrd	25	3.3	40	46
NE_PSDm.hrd	25	0.6	10	26
NE_PSDt.hrd	25	0.6	104	26
NE_F7_CD.hrd	25	1.9	32	34
NE_F7_LVDT	25	0.7	20	25
NE_F7_LVDT_Demod	3.125	1.9	0	134
			Total	**516**

Example: Vertical Control

- Four DSPs involved
- Users develop only control algorithms using a simple text interface
- Communication and synchronization transparent to users




```
NE_ID_Diag.hrd (Slot 5)
Input        Output       Filename       GUARD   Gain        Gname      @Frequency  When
ADD          dcOn                        yes     1           F0_DC_ENBL
dcOn         genSw           NULL        no      1           F0_POS_ON
genSw        ID_On           NULL        no      1           F0_ID_ON
genSw        Vert_On         NULL        no      1           F0_VPOS_ON
Vert_On      VID_On          NULL        no      1           F0_VID_ON
ADD          yL0                         no      -260        F0_Y_SET
Slot02_04    vl0             NULL        no      1
Slot04_01    va1             NULL        no      1
Slot04_02    va2             NULL        no      1
vl0          yL              NULL        no      1
va1          va1F      vAcc_Resp1.flt    no      -415560                 0          after
va2          va2F      vAcc_Resp2.flt    no      -380262                 0          after
Slot01_04    swLAG           NULL        no      1
 MAT                    vA.mat
{{  va1F            va2F }
 {  0.5             0.5  }                yAcc
 {  1               -1   }}               tcAcc
yL           yLE             NULL        no      1
yL0          yLE             NULL        no      -1
yLE          yLA1      elle75.flt        no      1                       0          after
yAcc         yLA1      acca75.flt        no      2.53e-08                1000       after
yLE          yLA2      elle75.flt        no      1                       0          after
yAcc         yLA2      acca75.flt        no      2.53e-08                1000       after
swLAG        swLA            NULL        no      1           swLA
SWITCH       yLA       yLA12             no      1
```

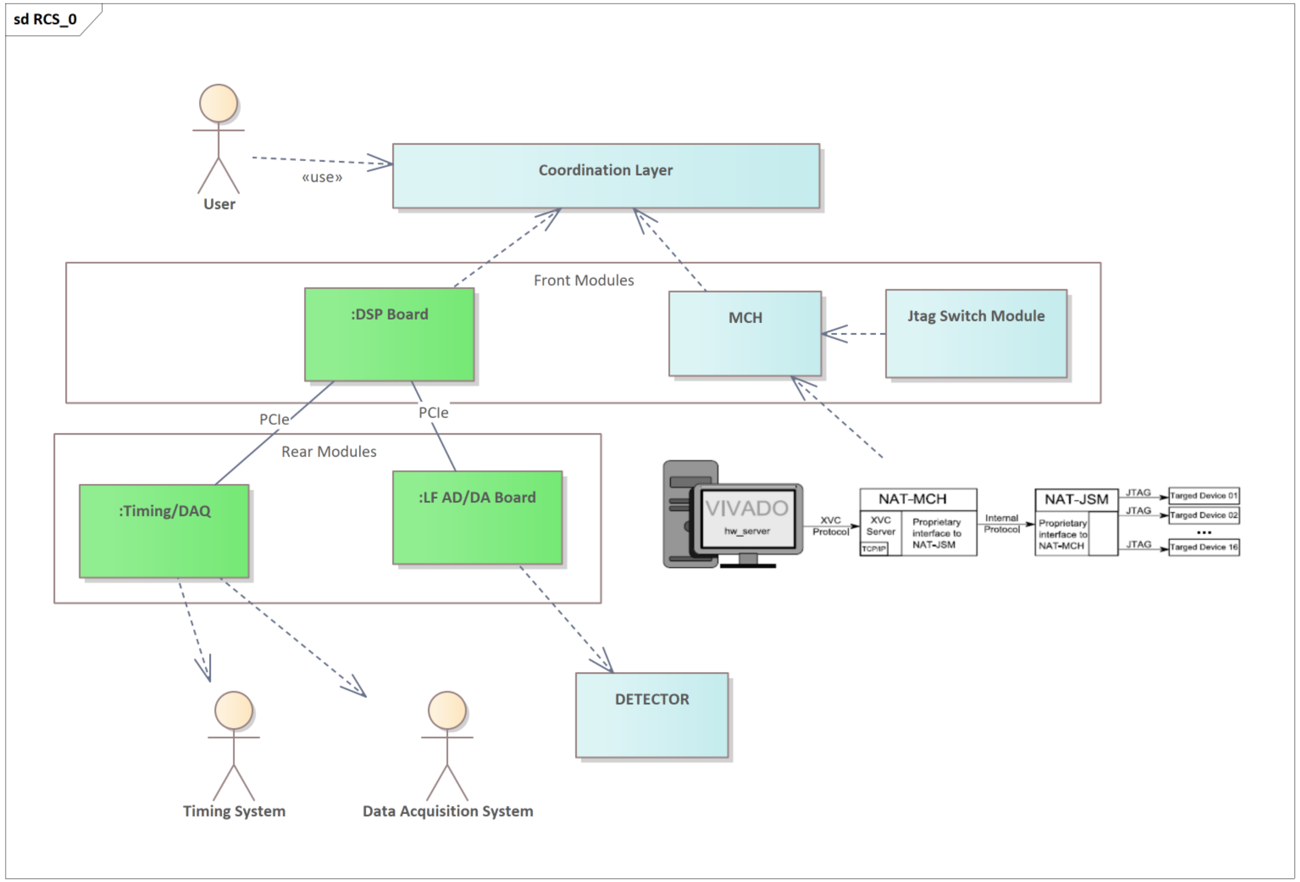
Data Flows

- Each of the 20 LCU could handle continuously:
  - More than 5000 high quality audio streams (320kbps)
  - 250 HD movies (3GB/hr)
  - 100 4K Ultra HD movies

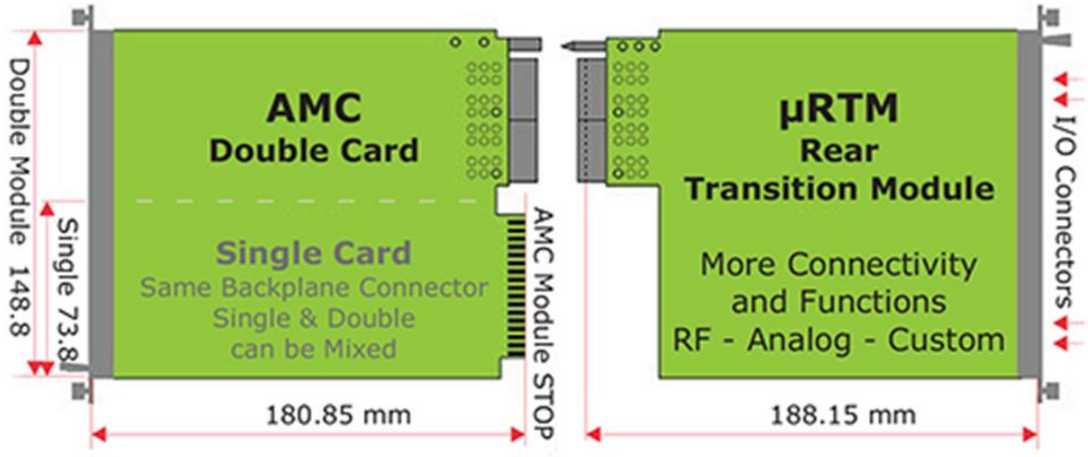
Slot	kPkts/s RX	kPkts/s TX	MB/s RX	MB/s TX
AMC_1/8-11	160	120	44	33
AMC_2/8-11	0	80	0	22
AMC_3/8-11	0	80	0	22
AMC_4/8-11	0	160	0	44
AMC_6/8-11	120	120	33	33
InterSwitch_1	200	120	54	33
InterSwitch_3	240	40	65	11
AMC_7/8-11	200	80	54	22
AMC_11/8-11	120	80	33	22
AMC_12/8-11	160	40	44	11
		Total	**207**	**207**

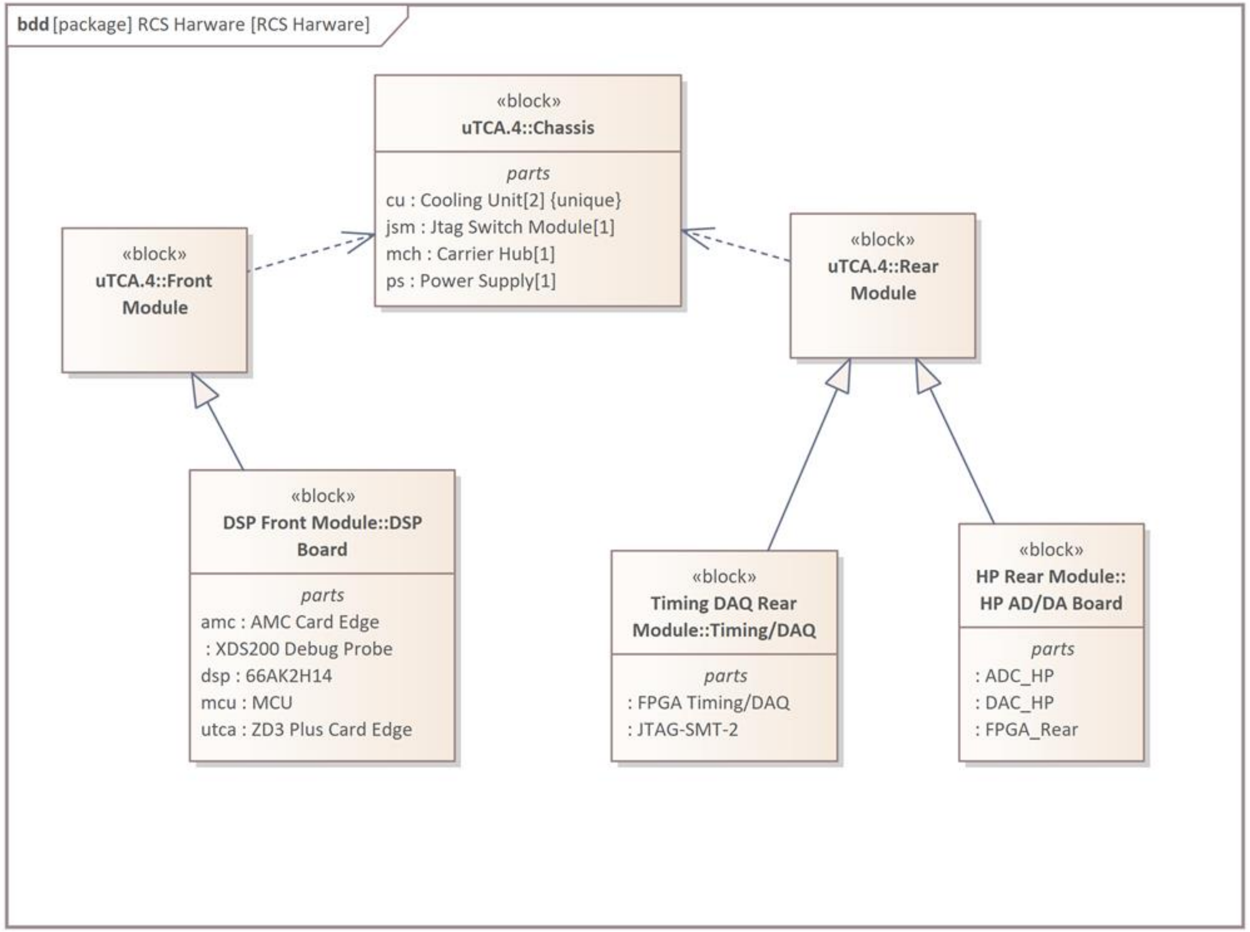
Upgrade running (prototypes ready soon)

- The upgrade of existing system has been recently funded by the Virgo Collaboration for complete replacement of control electronics.
- Virgo Subsystem Mirror Position Control
- Main differences
  - Fully compliant with MTCA.4
  - Replace DSPs with TI 66AK2H14 Multicore DSP+ARM® KeyStone™ II System-on-Chip (SoC)
  - Added flexibility with different rear modules
  - In collaboration with INFN Bologna (Timing/DAQ Module)



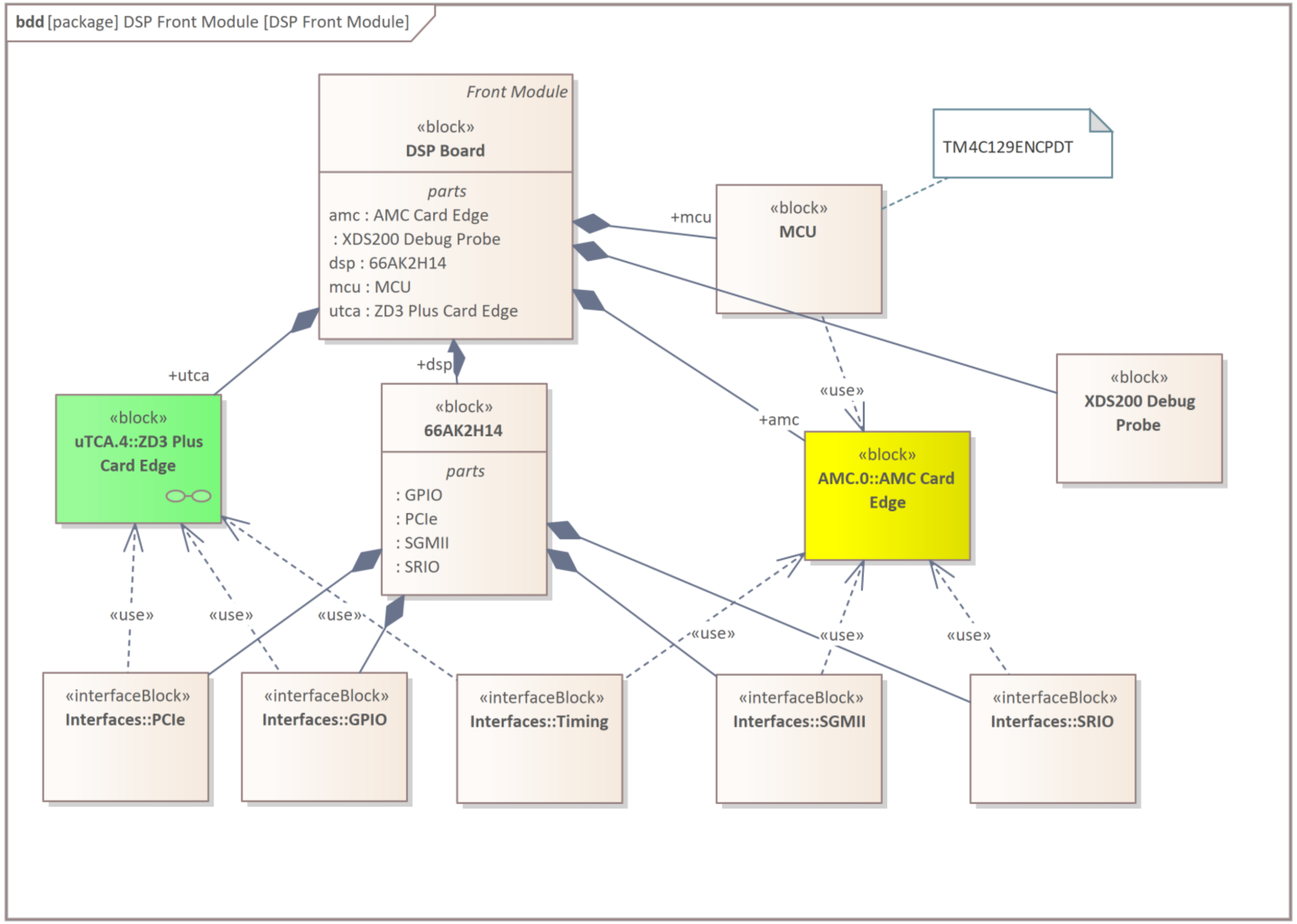
MicroTCA.4 (MTCA.4)

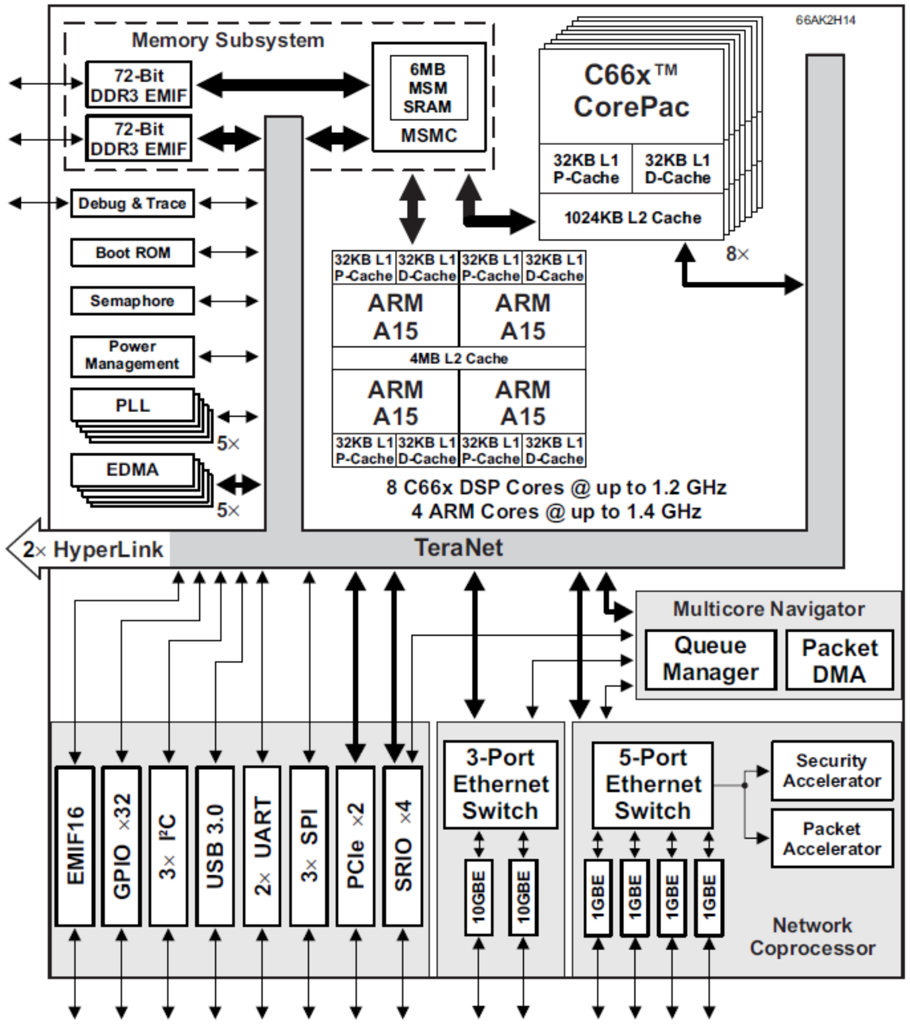




- Functionalities that in old system are merged into a single board have been split into three different modules:
  - DSP Front Module
  - AD/DA Rear Module
  - TimingDAQ Rear Module

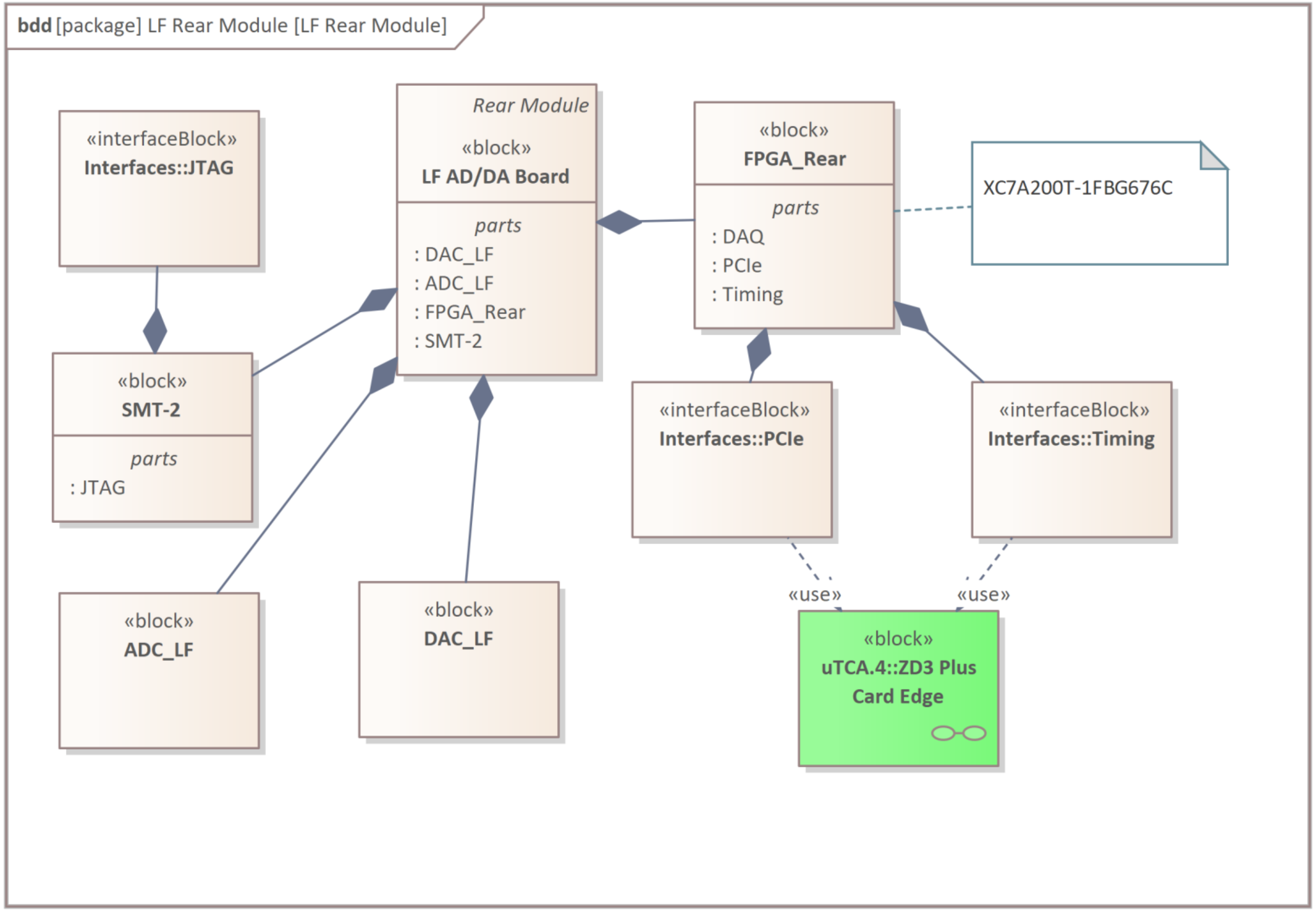
DSP Front Module





AD/DA Rear Module

- To speed up replacement, we keep same front end and data converters of system today in use
- Any further improvement postponed.



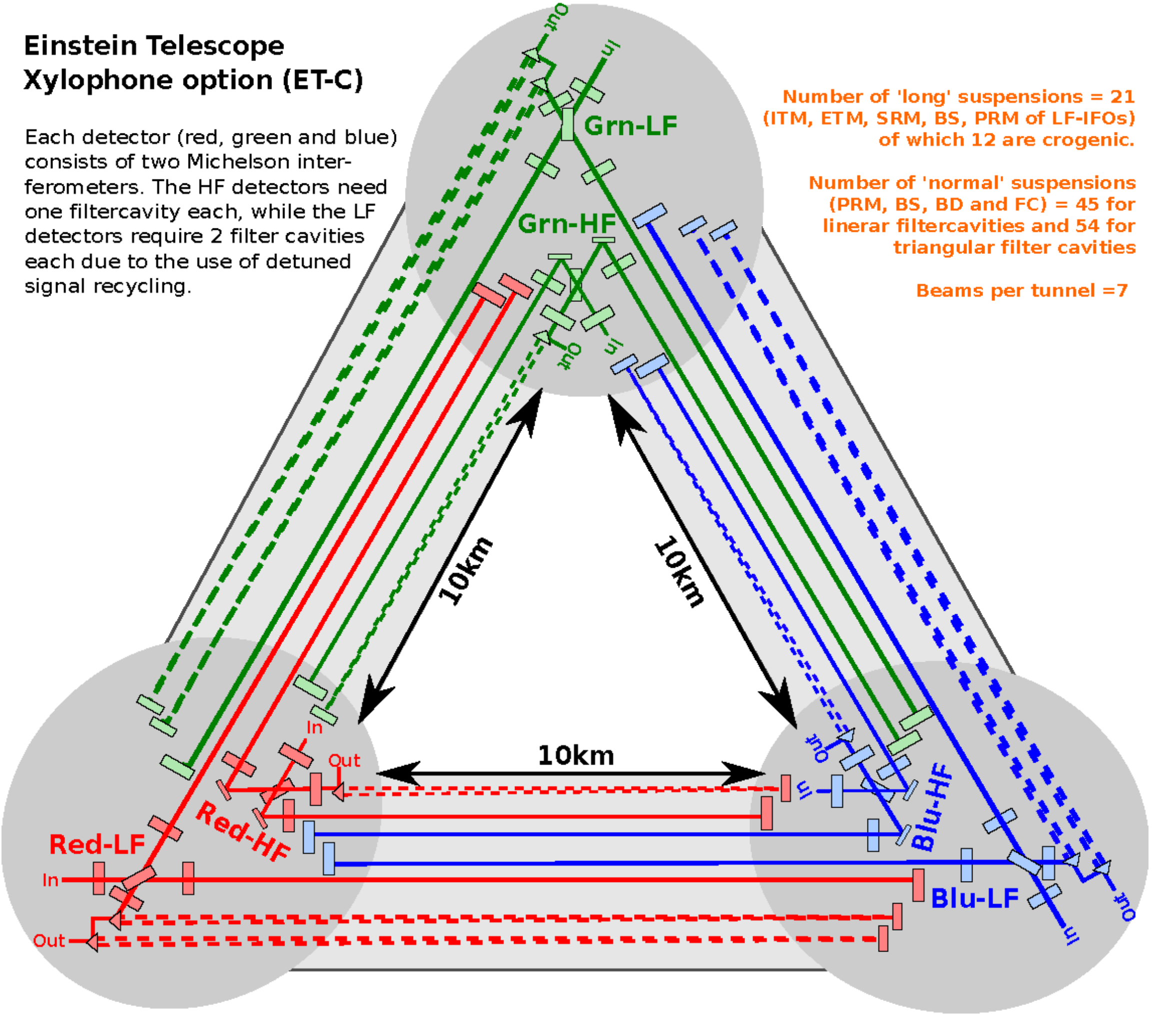
Future Upgrades

- We are starting from existing VIRGO system and evolve gradually towards future architecture where presumably A.I. will play a key role.
- Progress in Ethernet latency reduction will probably allow replacement of RapidIO.
- DSP+FPGA architecture would presumably evolve in GPU+FPGA architecture but total latency cannot be larger than the 40 us we have today (minimum delay).
- Key focusing is in high resolution converters and in lower low-frequency noise in general.
- Improving total latency down to 3-4 us with solutions based on fast data converters and FPGA will allow extending feedback loops unity gain frequencies and therefore possible applications range.

Einstein Telescope

Einstein Telescope
Xylophone option (ET-C)

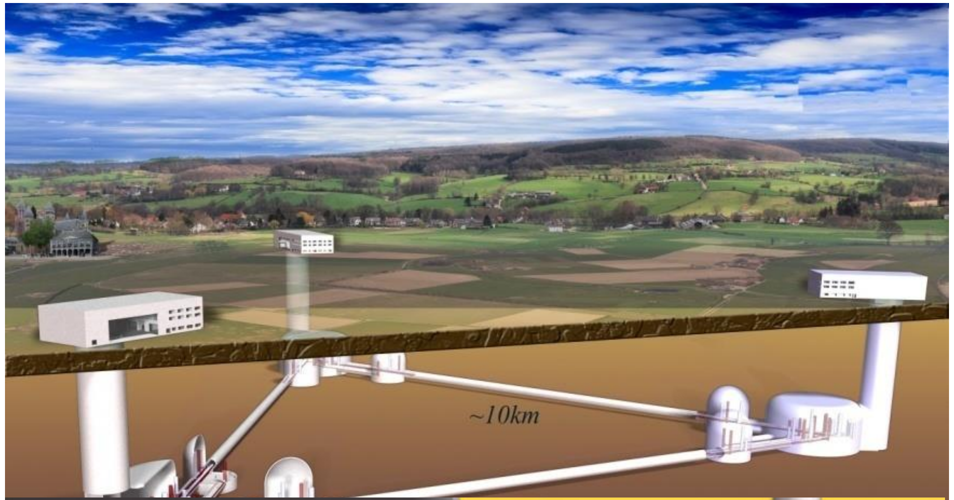
Each detector (red, green and blue) consists of two Michelson interferometers. The HF detectors need one filtercavity each, while the LF detectors require 2 filter cavities each due to the use of detuned signal recycling.

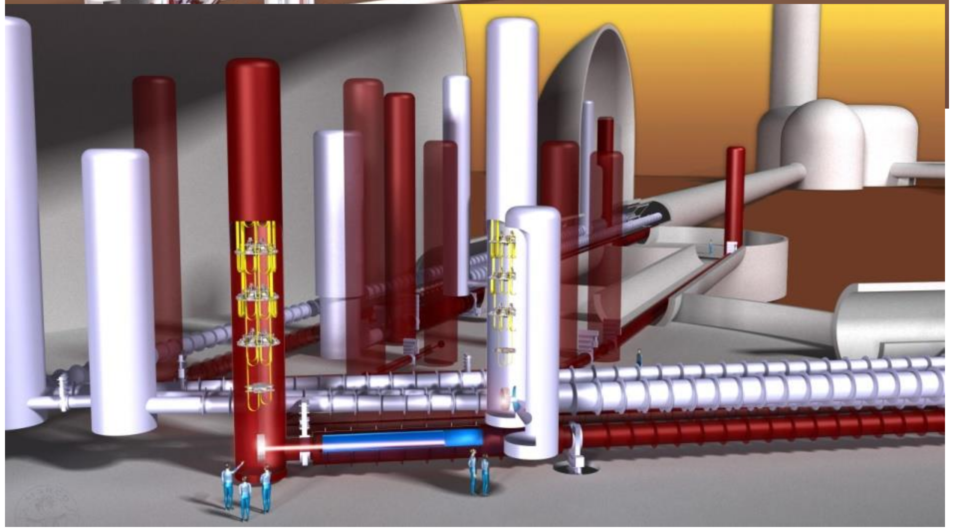


Number of 'long' suspensions = 21 (ITM, ETM, SRM, BS, PRM of LF-IFOs) of which 12 are crogenic.

Number of 'normal' suspensions (PRM, BS, BD and FC) = 45 for linerar filtercavities and 54 for triangular filter cavities

Beams per tunnel =7





Real Time Systems Design