Commissioning of the Type A suspensions control of KAGRA

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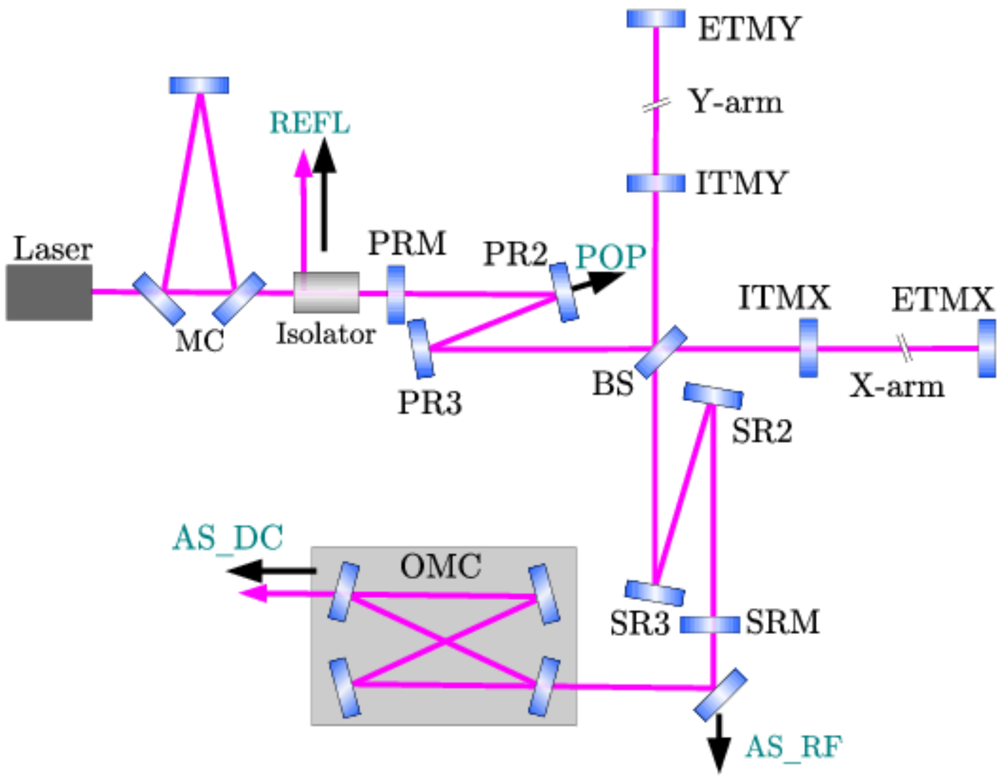
OUTLINE

- Introduction
- Seismic noise
- VIS
- Type A
- Noise budget of diagonalized sensors
- Blending technique
- Inertial damping: preliminary results
- Conclusion

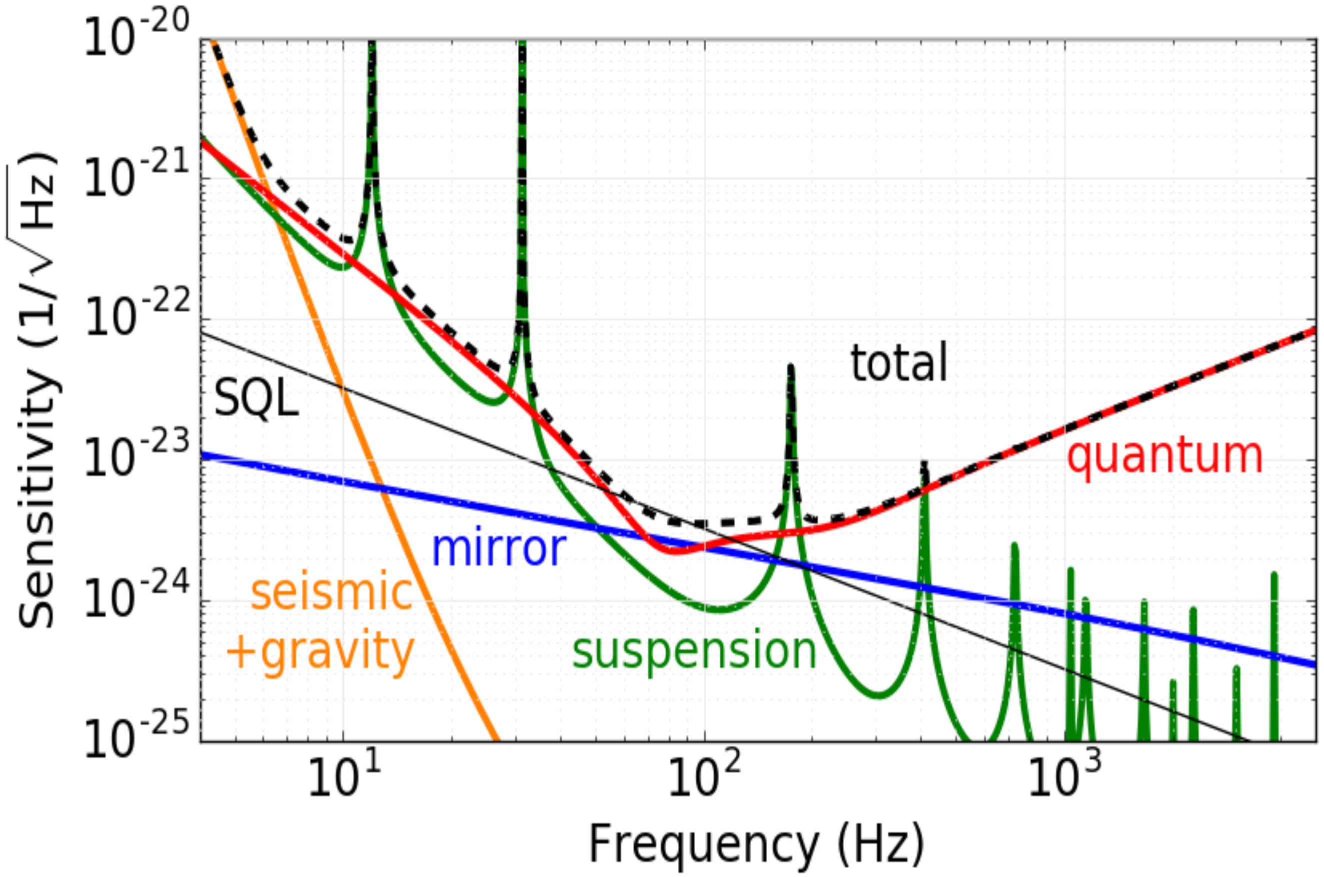
Introduction

- Gifu Prefecture, Japan
- 3km Arm Length
- Underground
- Cryogenic

Introduction



Target sensitivity of KAGRA



◆ Michelson ITF + 3 km long FP cavities

◆ Detection band [10 Hz, 10 kHz]

Limitations: **Seismic Noise, Shot Noise, Thermal Noise..**

Underground

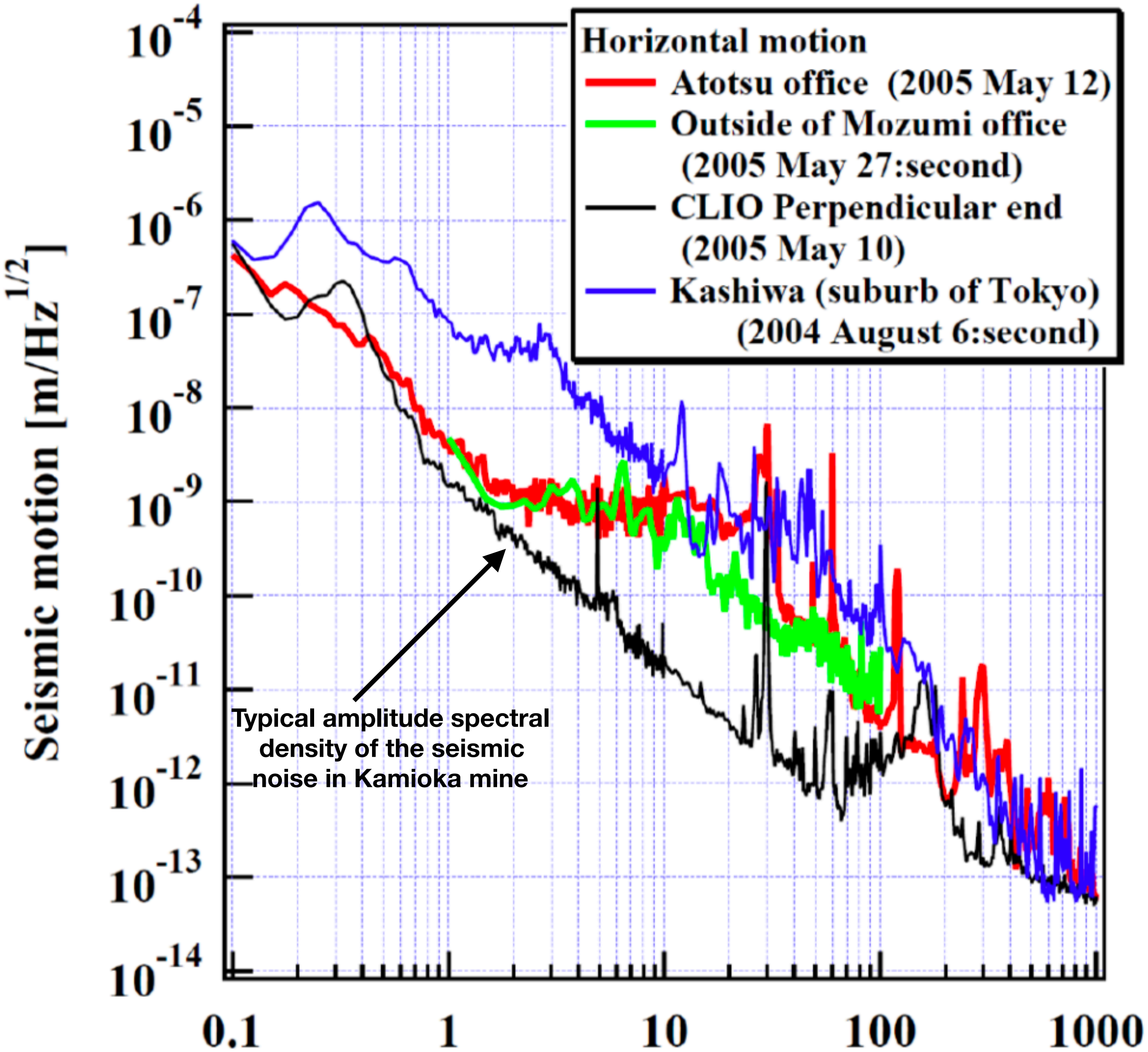
Reduce Seismic Noise

Cryogenic

Reduce Thermal Noise

Seismic Noise

KAGRA interferometer has been designed with the intent to develop an experimental apparatus for GW starting from 10 Hz.



- Seismic noise: is the dominant noise at low frequencies (below 10 Hz):

On Earth surface $\frac{10^{-6}m}{\sqrt{Hz}}$ @150 mHz **Underground** $\frac{5 \cdot 10^{-7}m}{\sqrt{Hz}}$

- In detection band > 10 Hz the seismic noise reaches the values

On Earth surface $\frac{10^{-9}m}{\sqrt{Hz}}$ **Underground** $\frac{10^{-12}m}{\sqrt{Hz}}$

To detect the little displacement due to a GW $\frac{10^{-18}m}{\sqrt{Hz}}$

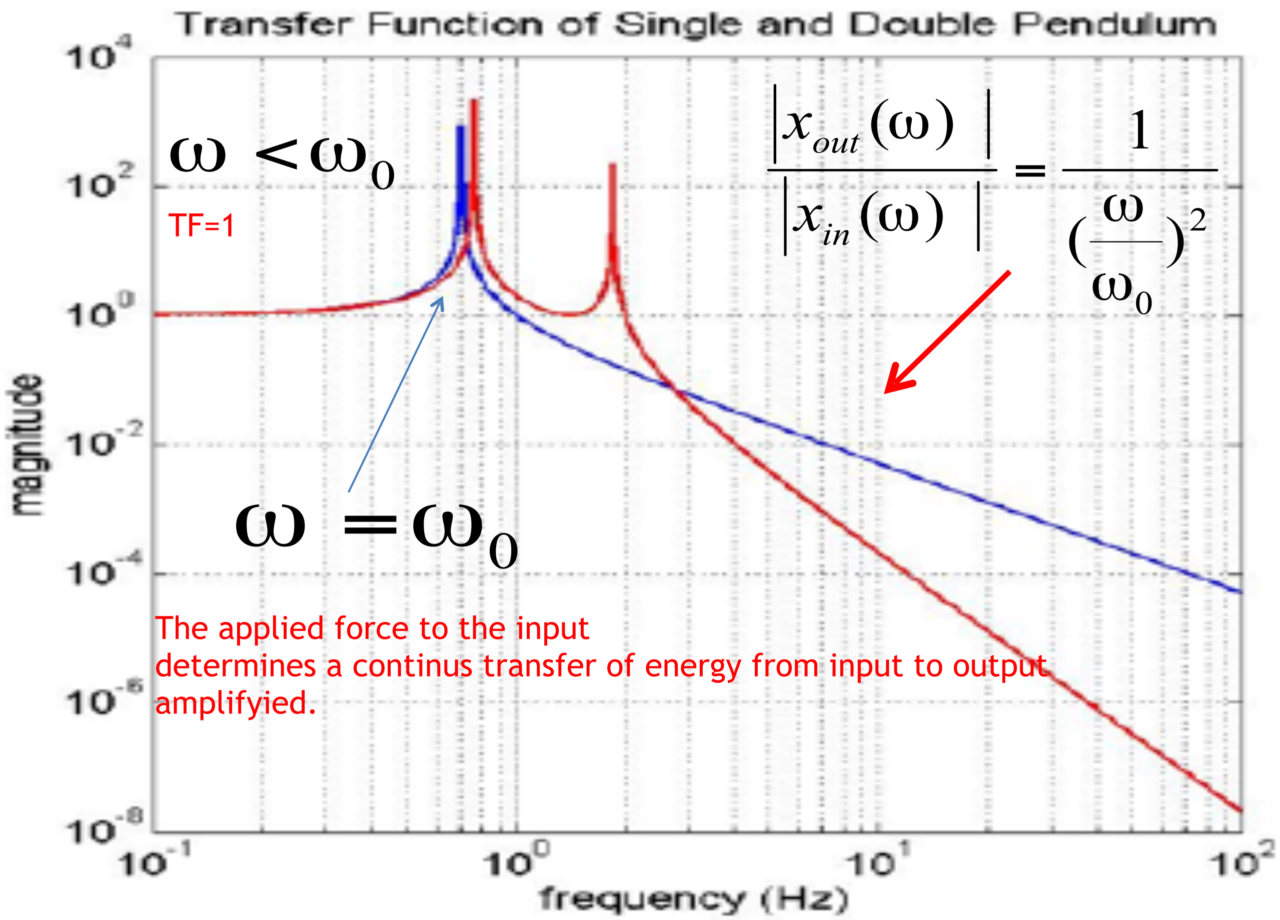
A seismic isolation with a capability attenuation ~ 10 orders of magnitude is needed!!!

- **Free-falling TM (Test Mass)**
- **Isolation from Seismic Noise**

Mechanical attenuators of the seismic vibrations

A good approximation of the free falling mass is represented by the simple pendulum

$$\frac{|x_{out}(\omega)|}{|x_{in}(\omega)|} = \frac{1}{1-(\frac{\omega}{\omega_0})^2}$$

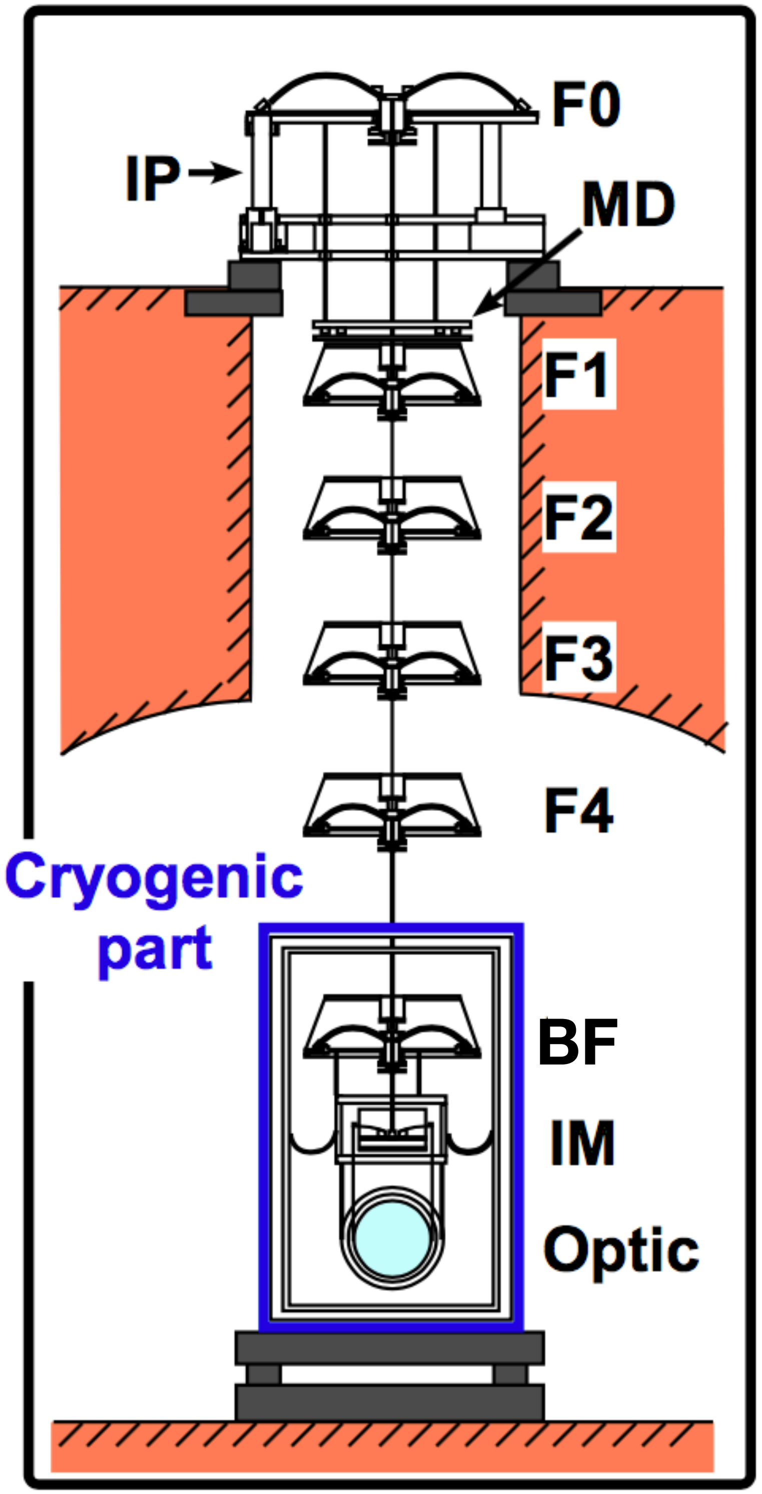


Cascading 2 harmonic oscillators

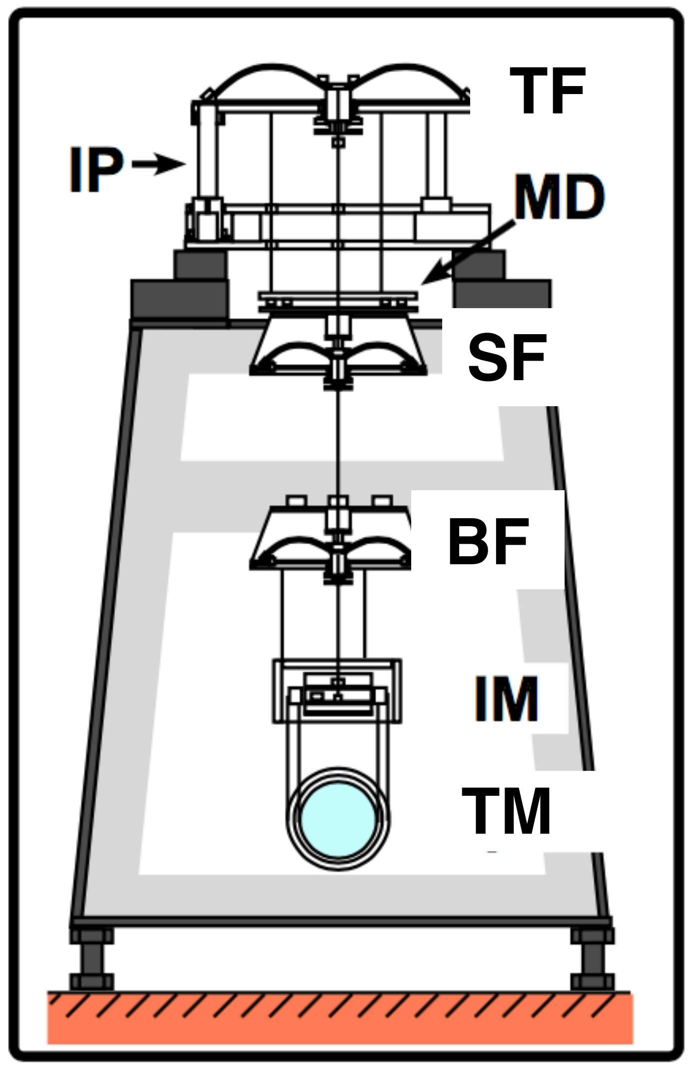
$$\frac{|x_{out}(\omega)|}{|x_{in}(\omega)|} = \frac{A}{(\omega)^4} \qquad A = \omega_1^2 \cdot \omega_2^2$$

Solution adopted in KAGRA is based on the idea to replicate a certain number of harmonic oscillators of length ~ 2 m to obtain a sophisticated mechanical structure: **<u>VIS suspension system</u>**

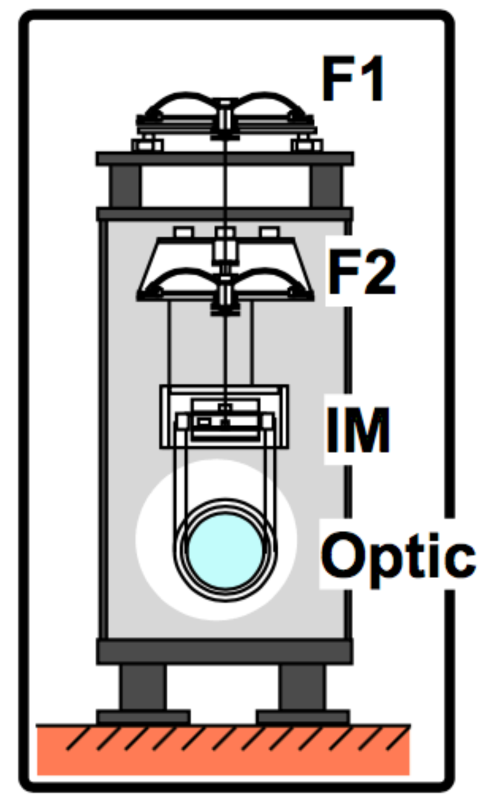
VIS Suspension Systems



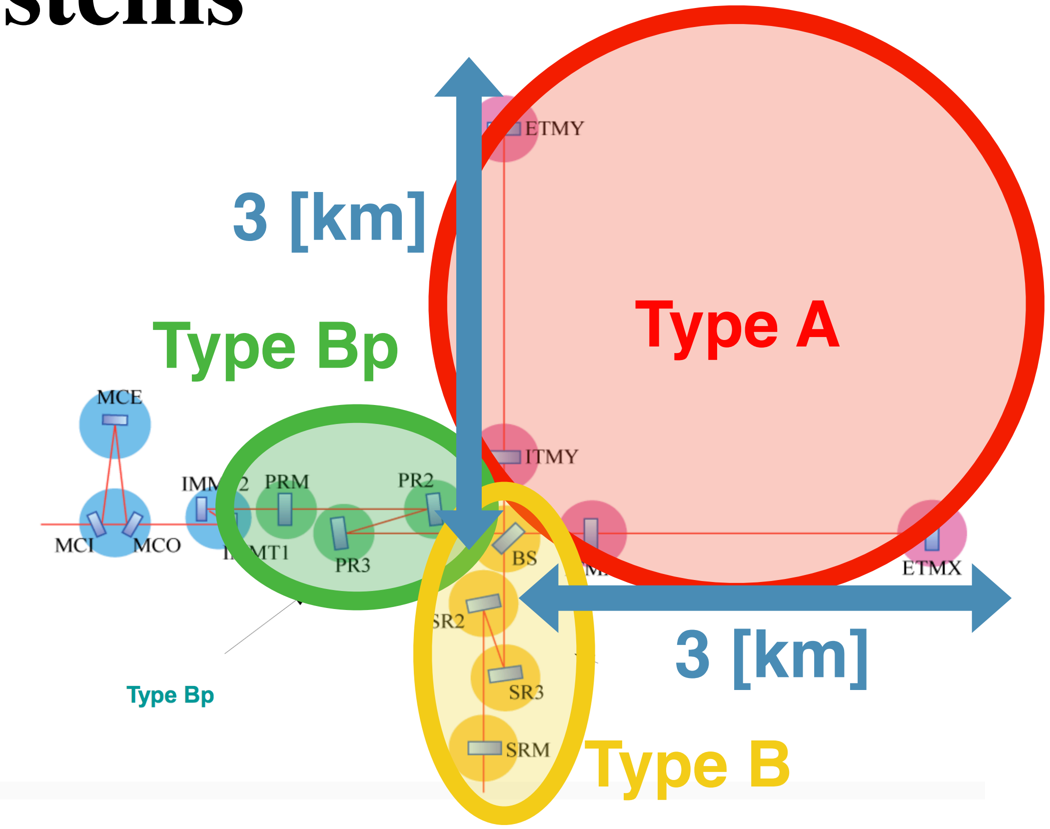
Type-A



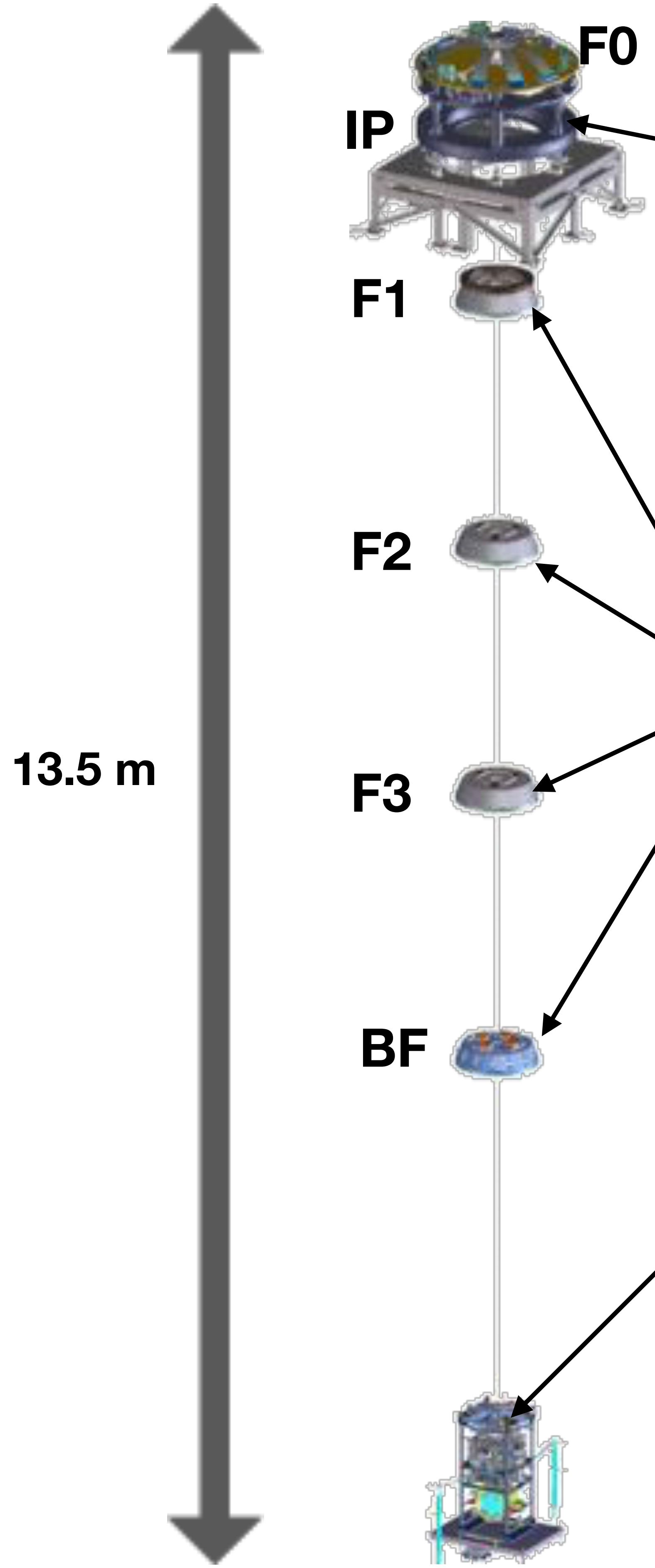
Type-B



Type-Bp



Type A suspension



- **Pre-isolation stage:**
  - the Inverted Pendulum (IP-3 legs structure)
  - mechanical filter (F0)

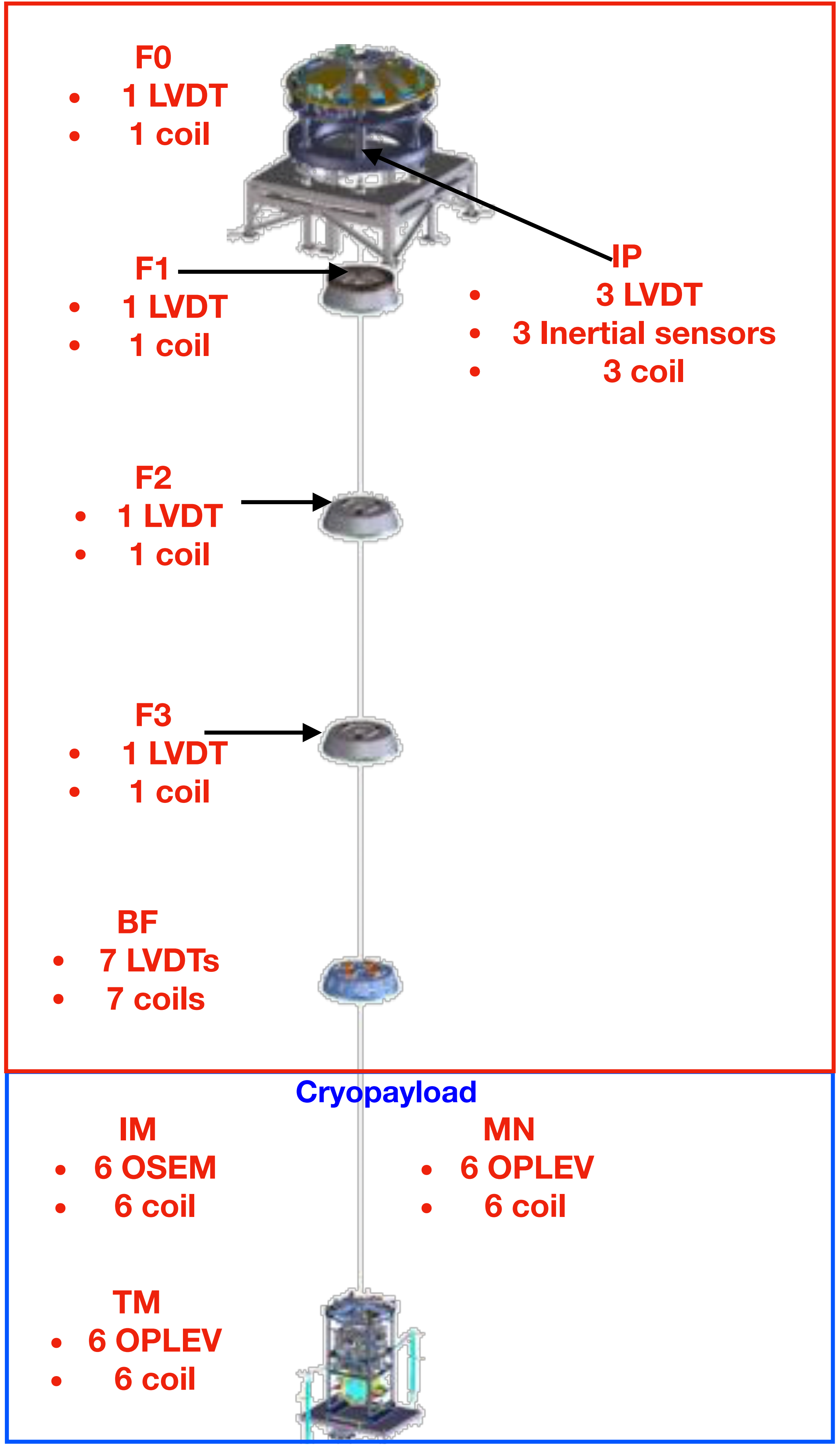
The system provides a good seismic isolation in horizontal direction (IP) as well as in the vertical one (GAS Filters).

- **The passive multi-stage pendulum chain:**
  - Four mechanical GAS filters (F1, F2, F3, BF Steering Filter)

Vertical modes of the mechanical filters are below 1 Hz

- **The cryopayload:**
  - Platform
  - Marionette
  - Intermediate mass
  - Test mass

The normal modes of the pendulum mechanical structure are confined in low frequency region (below 2Hz)



Type A suspension: Sensors and actuators

The **feedback control** could be implemented in different points:

- Inverted Pendulum
- vertical GAS filters
- Bottom filter
- Marionette and Test Mass

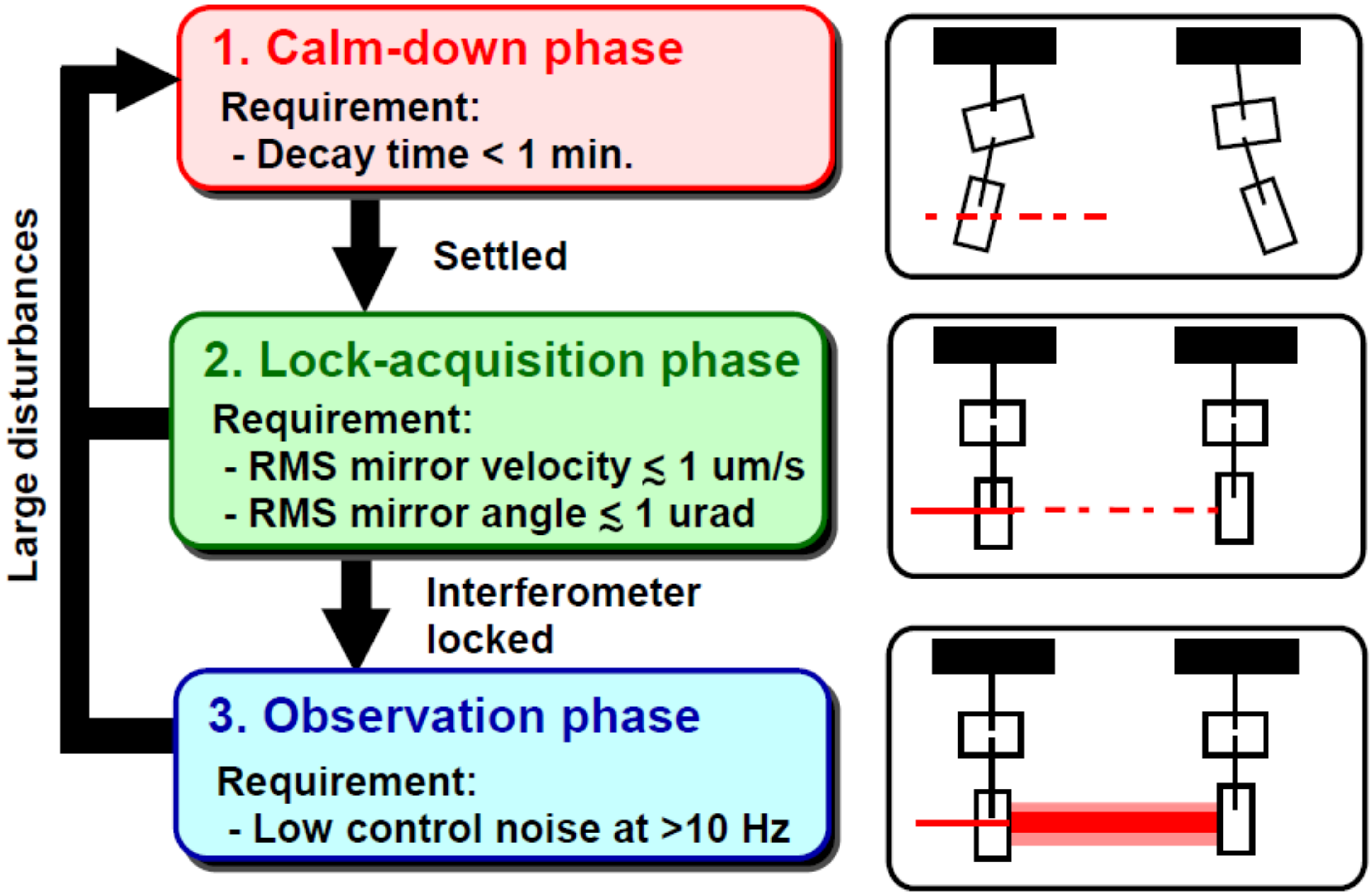
1. **Control on IP to reduce the motion in L, T and Y**
2. **Control on BF to reduce the Yaw motion of the chain**
3. **Control on top stage and GAS filter to reduce the Vertical motion**
4. **Control on the Marionette and Test Mass to reduce the Yaw and Pitch motion**

We focus our attention on the points 1 and 2.

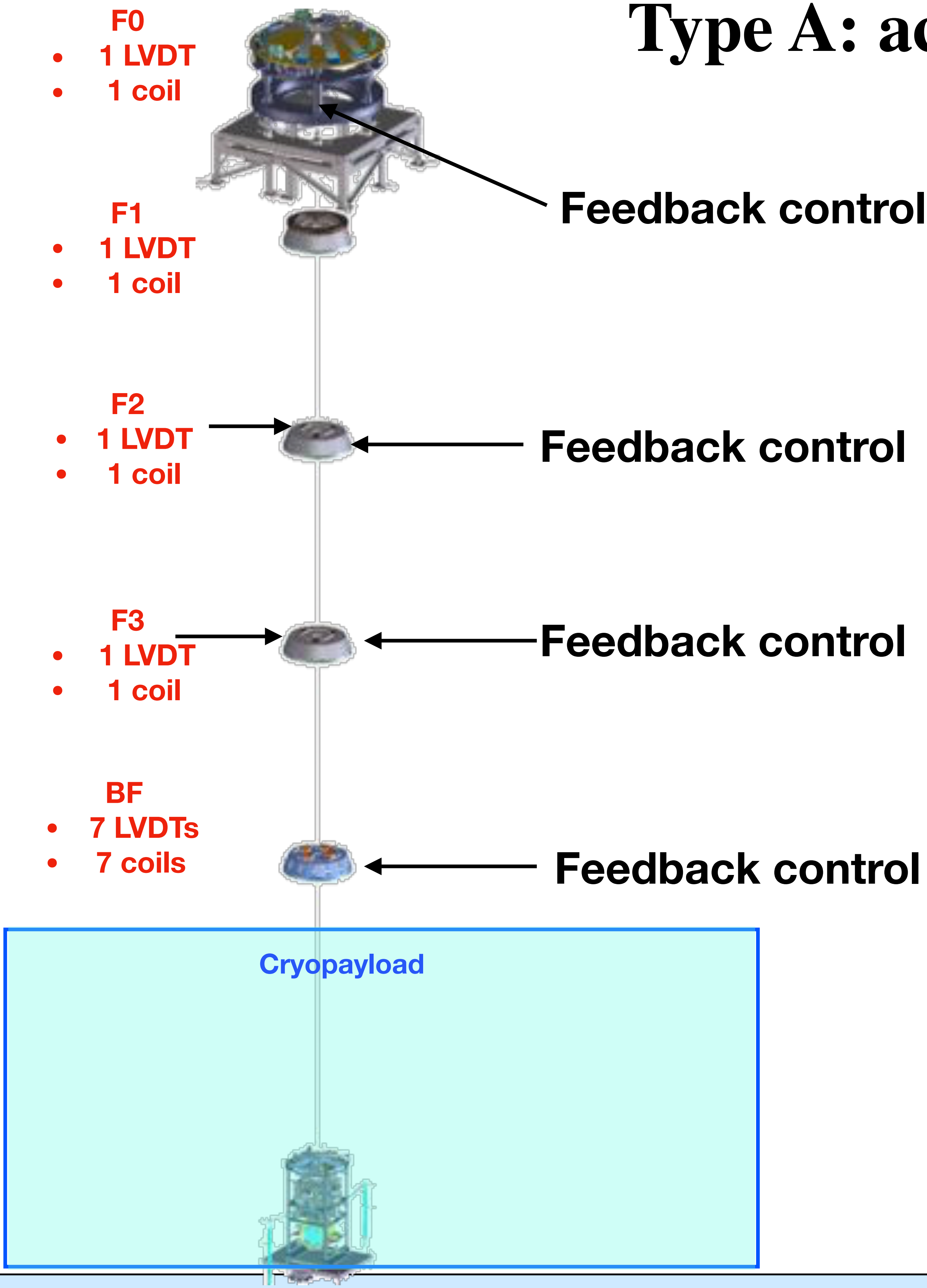
For IP, BF and GAS Filters the adopted control strategies are:

- On the IP is implemented an Active Mode Damping of the resonance modes and for seismic noise reduction
- On the BF and on the GAS filters a viscous damping control of the resonance modes is implemented

Type A suspension:requirements



Type A: actuation points



Calm down phase:
- IP control

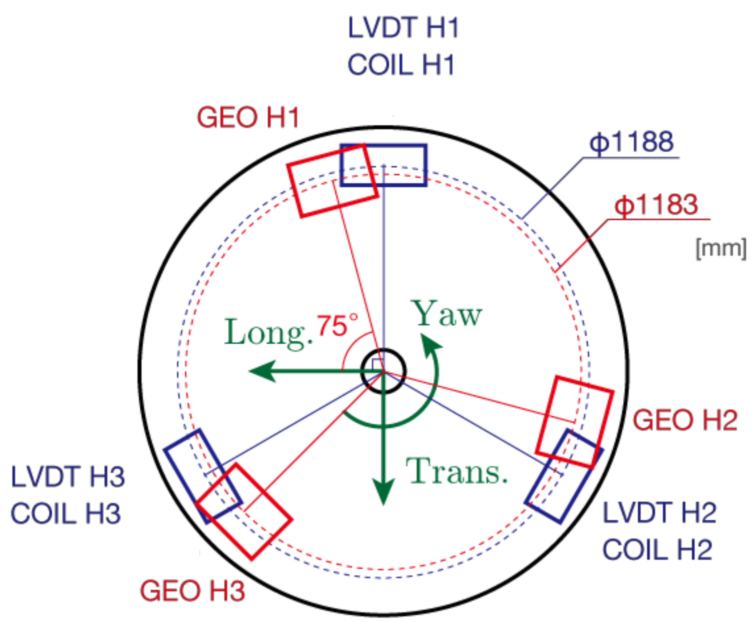
Calm down phase:
- GAS filters control

Calm down phase:
- BF Y control

Type A suspension: sensors and actuators

To implement the Damping control on the IP and on the BF first we build the diagonalized sensors and actuators in the (L,T,Y) base

IP



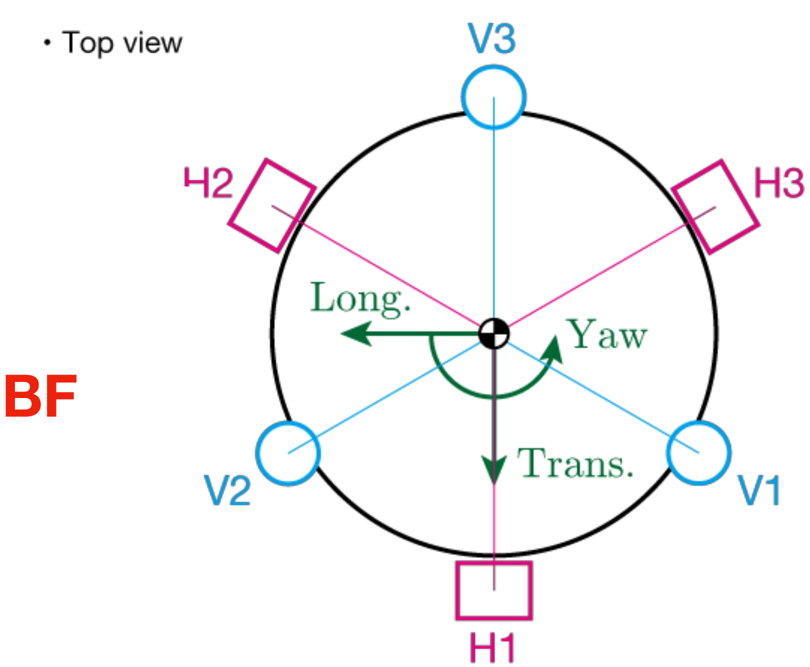
LVDTs sensing matrix

sensor base: (H1, H2,H3) → *Geometrical transformation* → **Euler base: (L, T,Y)**

Read-out Driving matrix

Actuators base: (H1, H2,H3) → *Noise injection from each actuator (@2 Hz line)* → **Euler base: (L, T,Y)**

BF



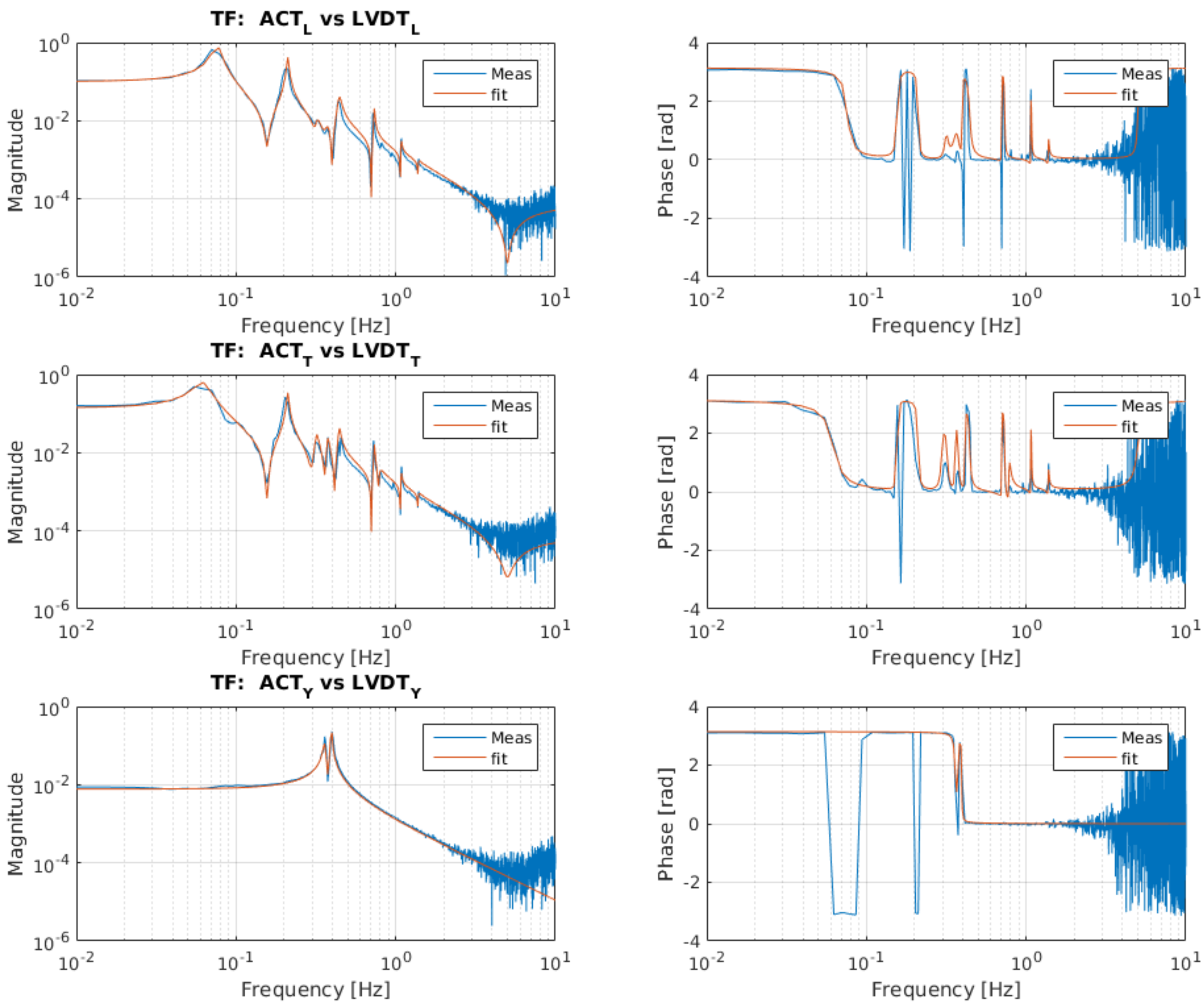
LVDTs sensing matrix

sensor base: (H1, H2,H3) (V1, V2,V3) → *Geometrical transformation* → **Euler base: (L, T,Y) (P, R,V)**

Driving matrix

Actuators base: (H1, H2,H3) (V1, V2,V3) → *Geometrical transformation* → **Euler base: (L, T,Y) (P, R,V)**

Inverted Pendulum (IP) mechanical transfer functions

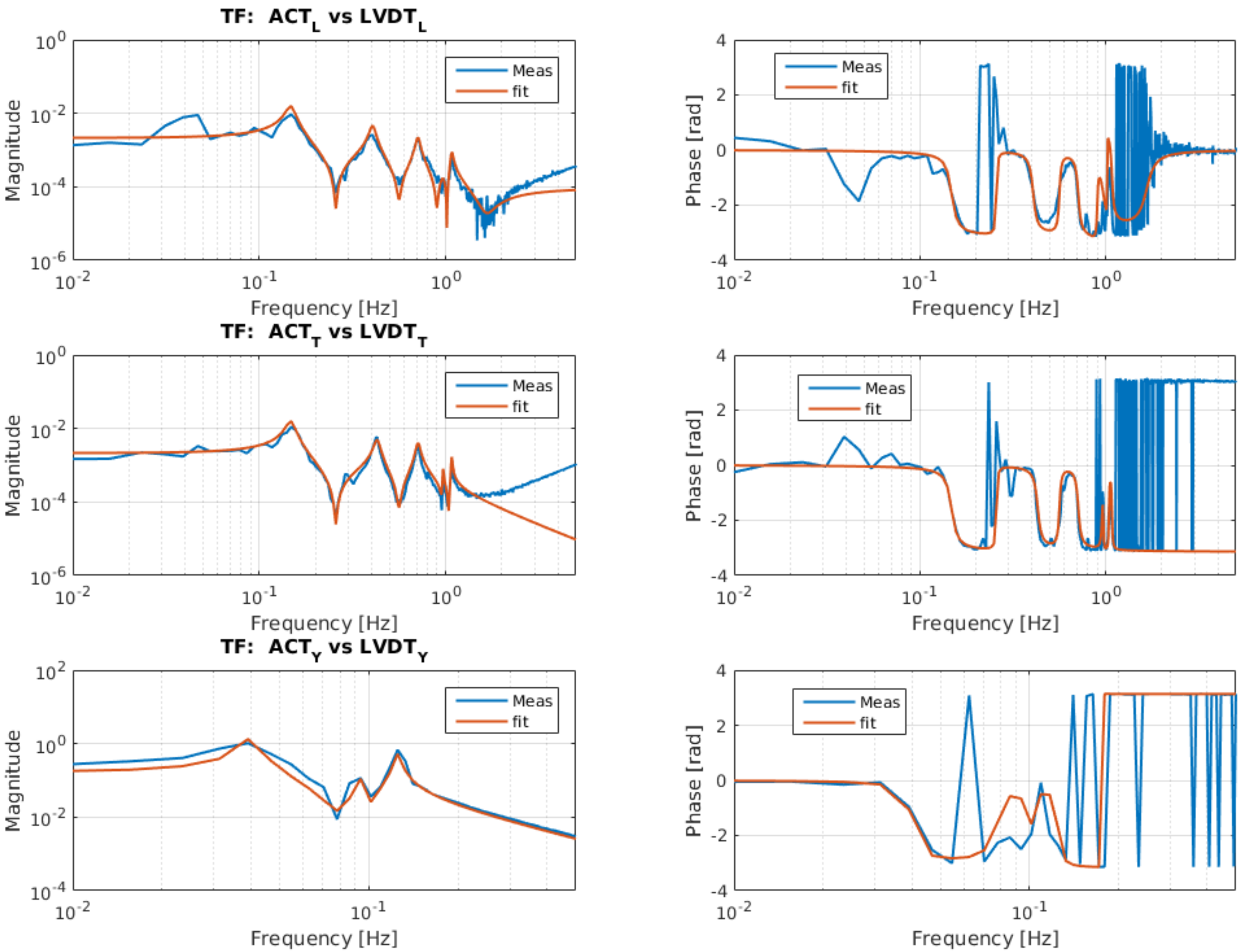


IP: L mode 0.067 Hz

IP:T mode 0.067 Hz

IP:Y mode 0.4 Hz

Bottom Filter (BF) mechanical transfer functions



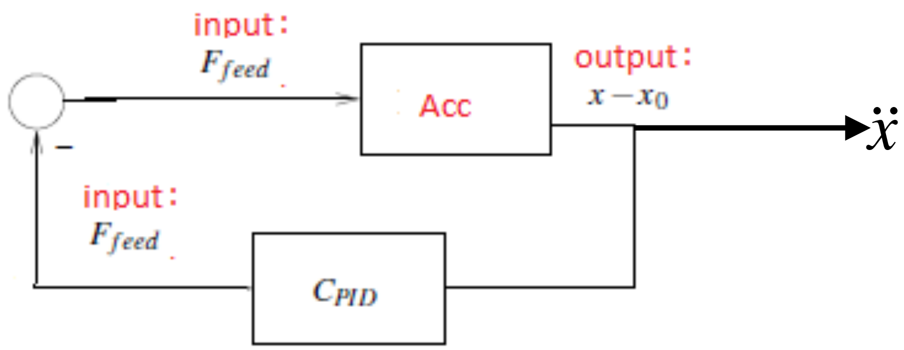
BF: L mode 0.148 Hz

BF:T mode 0.148 Hz

BF:Y mode 0.04 Hz

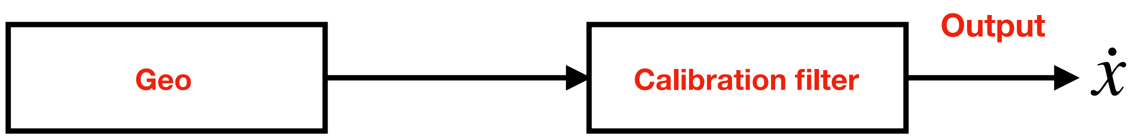
Type A: inertial sensor (I)

Input suspensions (ITMX,ITMY):
3 accelerometers



Output signal : acceleration

End suspensions (ETMX,ETMY):
3 Geophones

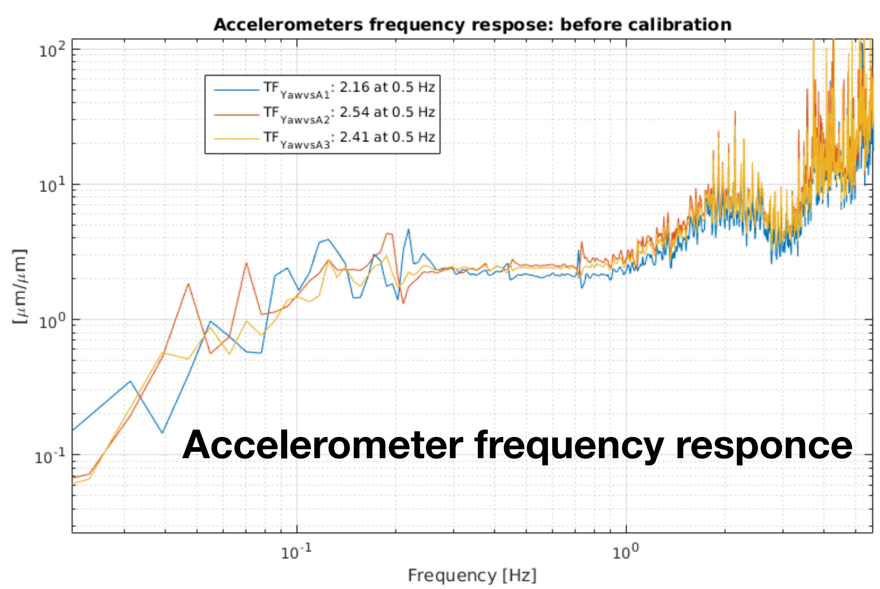


Output signal : speed

In both cases we need of the inter-calibration with the LVDT signals!

Injecting white noise along the IP Yaw degree of freedom and to measure the transfer function:

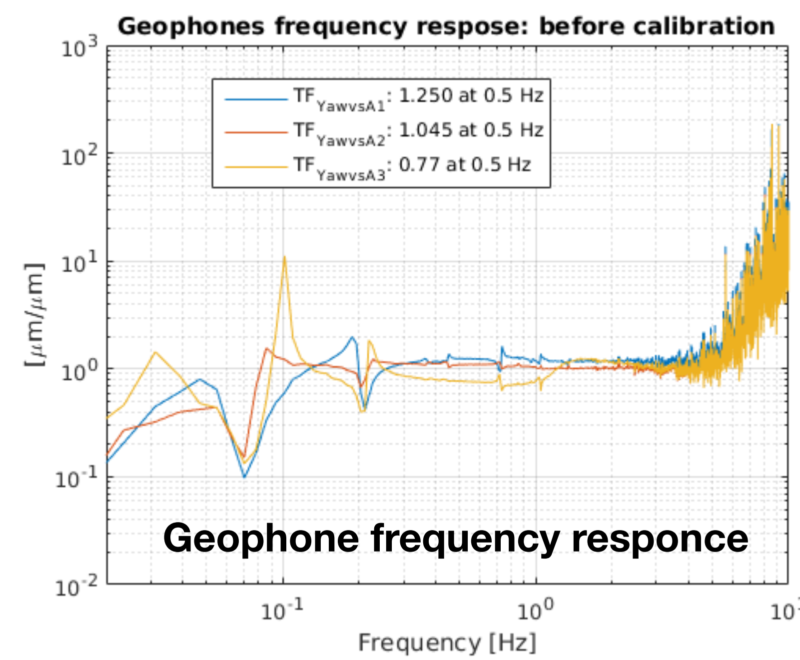
$$TF_{yaw_{acc_i}} = \frac{Yaw_{lvdt} \cdot r}{\frac{acc_i}{\omega^2}}$$



where i=1,2,3 and r is the linear distance of each inertial sensor from the center of IP

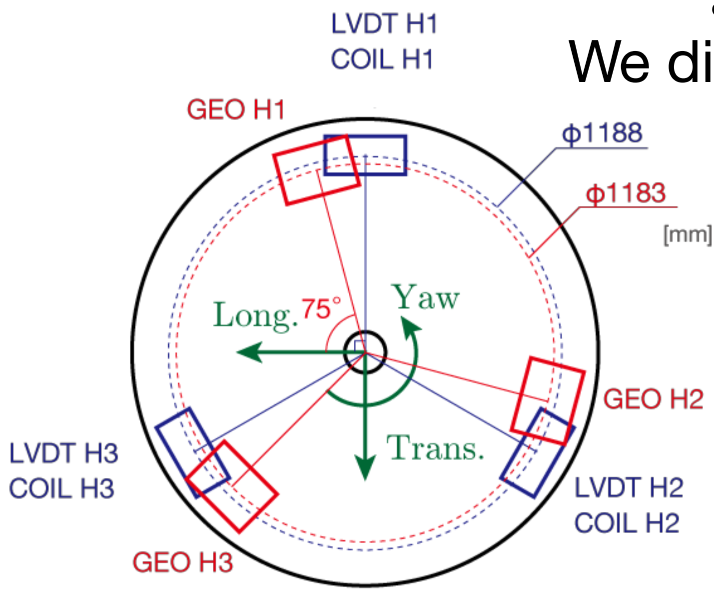
Yaw is an isotropic motion: these TFs should be equals.

$$TF_{yaw_{geo_i}} = \frac{Yaw_{lvdt} \cdot r}{geo_i}$$



Type A: inertial sensor (II)

We diagonalize the inertial sensors in the (L,T,Y) base.



Read-out Sensing matrix

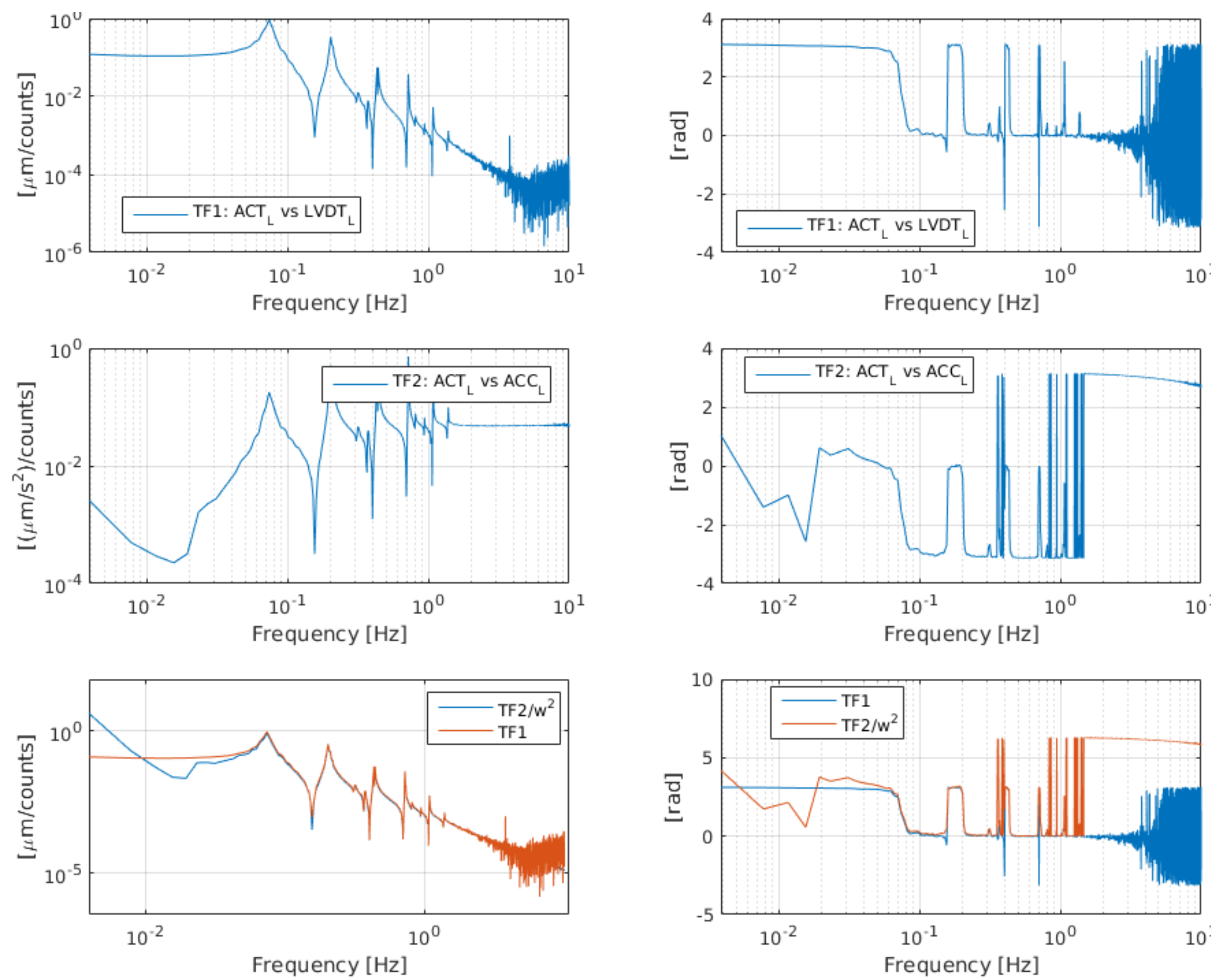
Sensors base: (H1, H2,H3) → ***Noise injection from each diagonalized actuator (@2 Hz line)*** → **Euler base: (L, T,Y)**

The sensor response is equalized.

LVDT: L

ACC: L

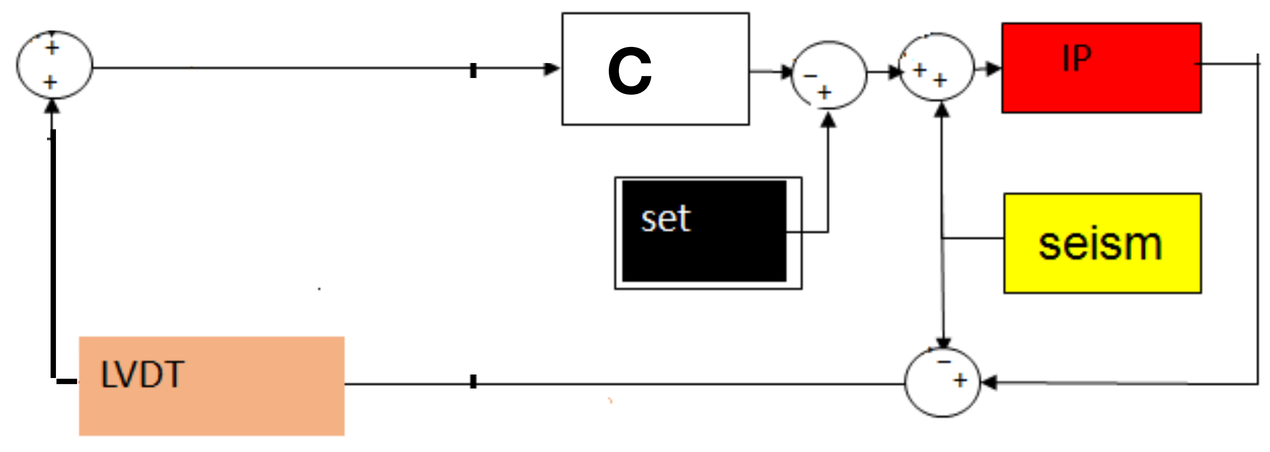
ACC & LVDT: L



Type A: Damping control

IP= mechanical system

Feedback control scheme



LVDT= is the sensor monitoring the displacement

$$x_{lvdt} = x_{IP} - x_0$$

x_0 **is the ground motion**

C= is the damping filter

set= is the set point

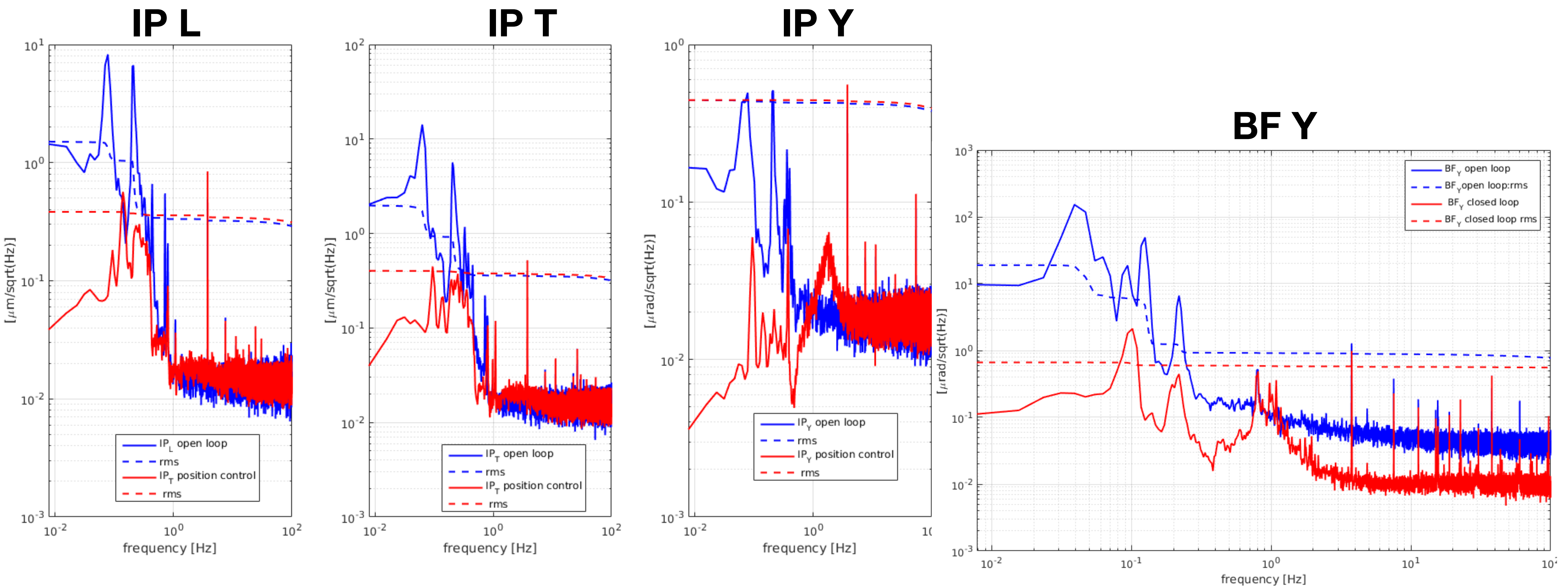
The closed loop signal is defined as

$$\tilde{S}_{iv}^{CL}(\omega) = \frac{\tilde{S}_{iv}(\omega)}{1 - \tilde{M}_i(\omega) \cdot \tilde{C}_i(\omega)}$$

In this configuration:

IP LVDT signal =
Error signal in L, T ,Y

Type A: Damping control



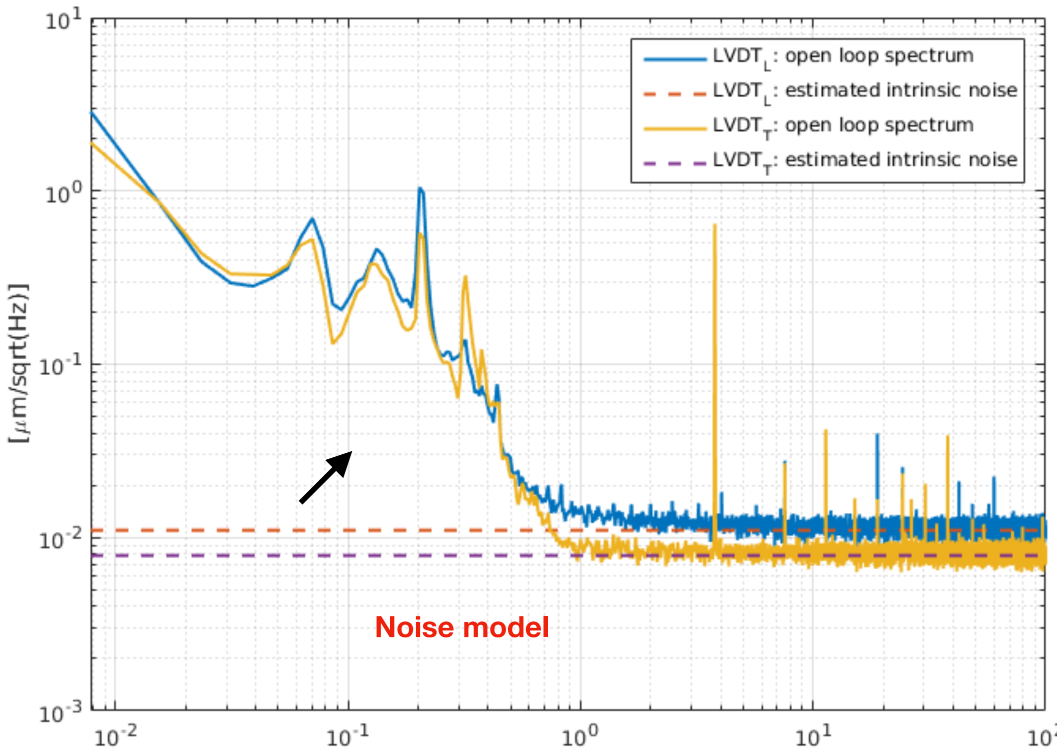
	L RMS [μm]	T RMS [μm]	Y RMS [μrad]
IP(OL)	**1.5**	**2**	**0.5**
IP (CL)	**0.4**	**0.4**	**0.5**
BF (OL)			**30**
BF (CL)			**0.7**

In this configuration we are limited by seismic noise

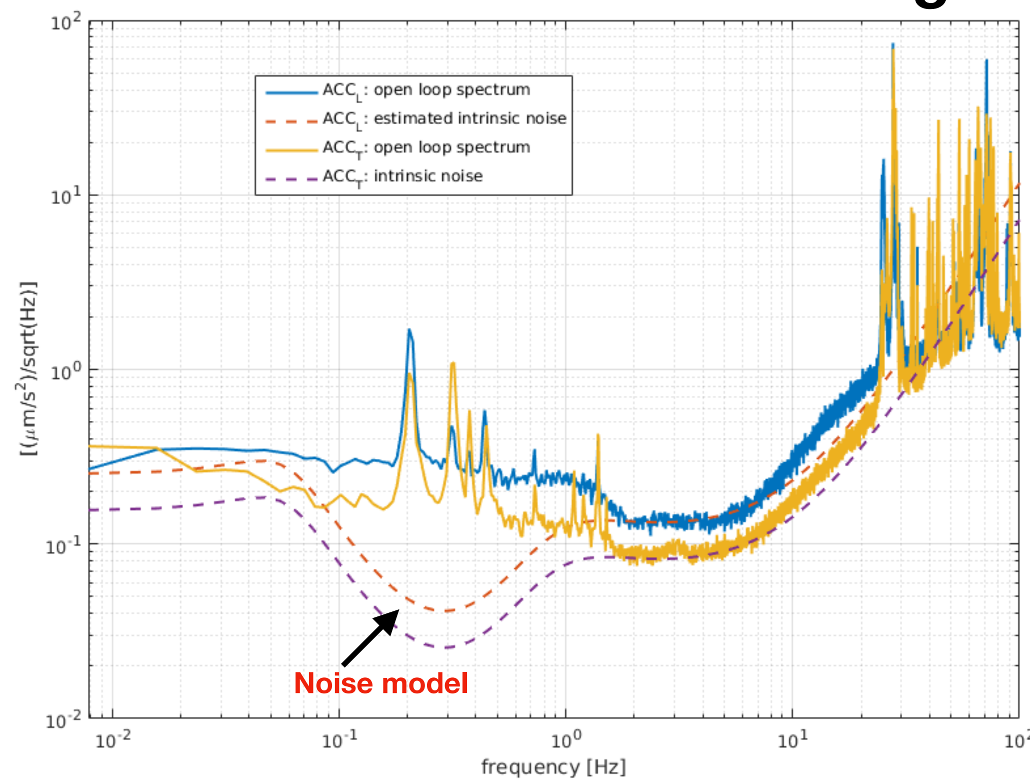
Type A: seismic noise reduction and Inertial control

Let's consider the sensors in the L,T,Y base

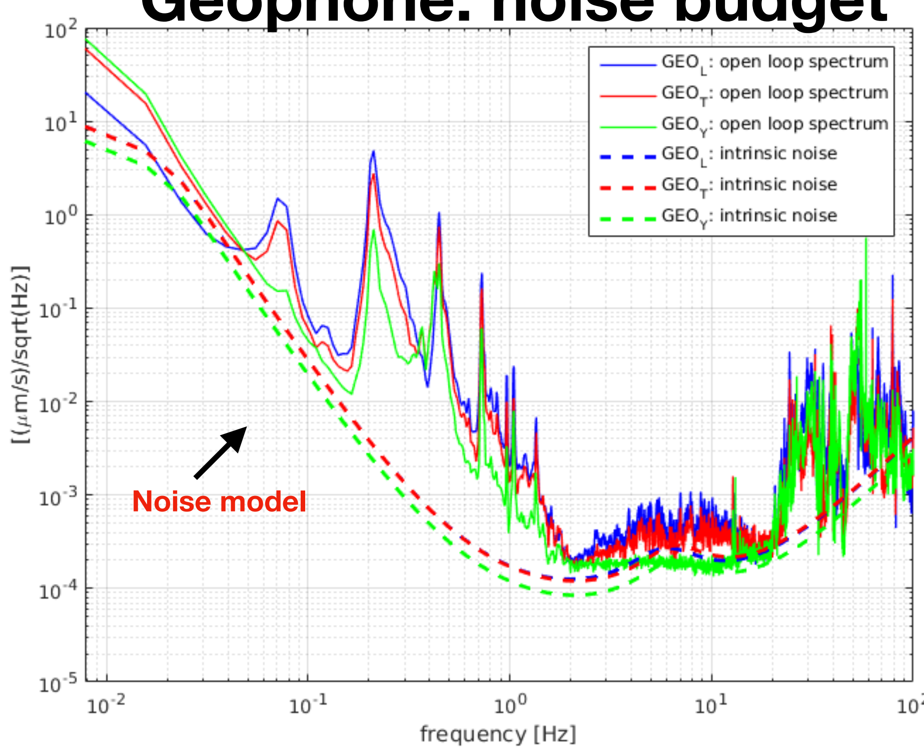
LVDT: noise budget



Accelerometer: noise budget

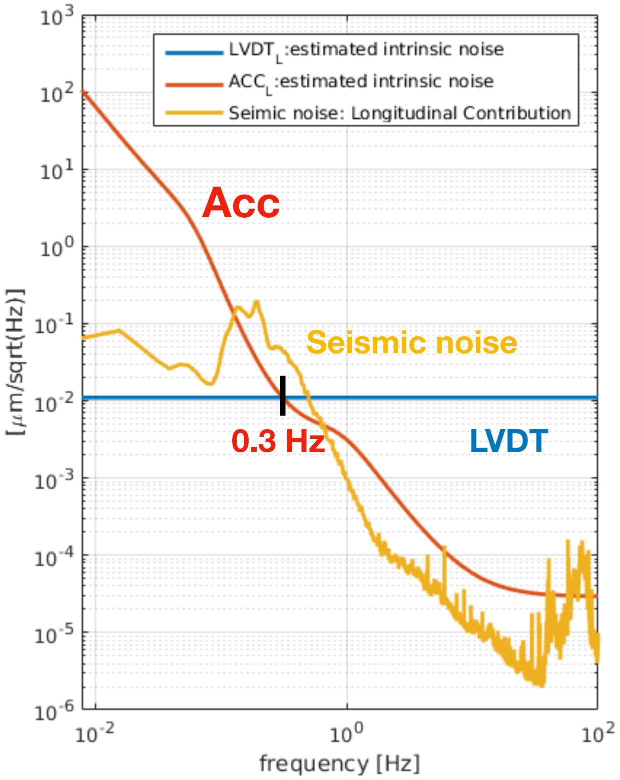


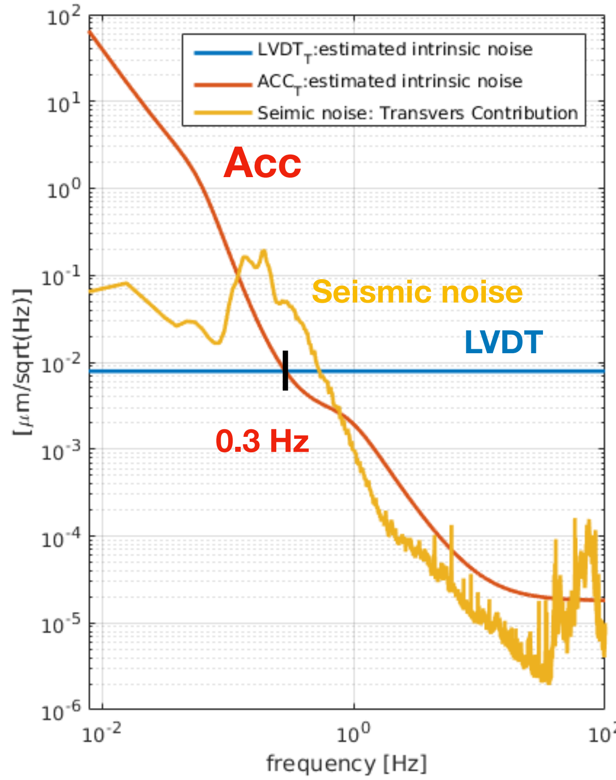
Geophone: noise budget



Sensors spectrum signal (LVDT, accelerometer, geophone) versus intrinsic noise (model)

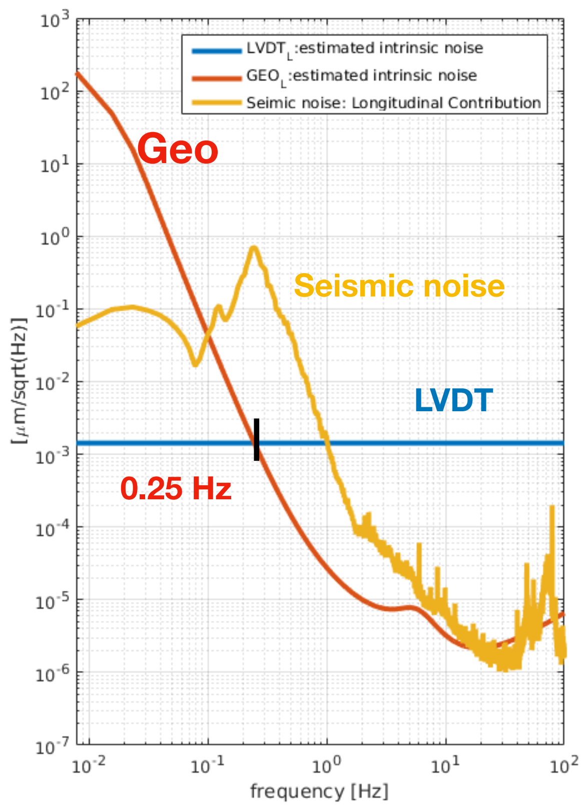
Inertial control: noise budget (II)

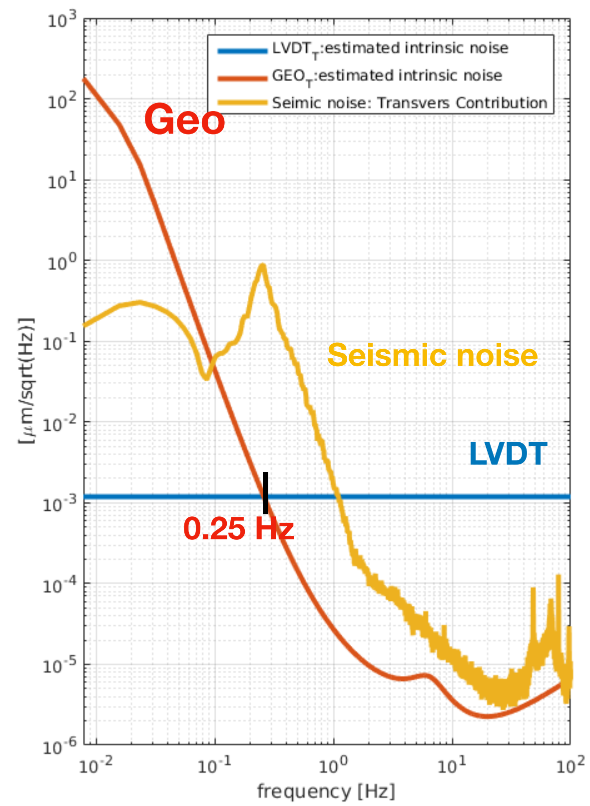




In the range [0.1,0. 5] Hz, the LVDT signal is spoiled by seismic noise

Below 0.3 mHz, the accelerometer noise is dominant





Below 0.250 mHz, the geophone noise is dominant

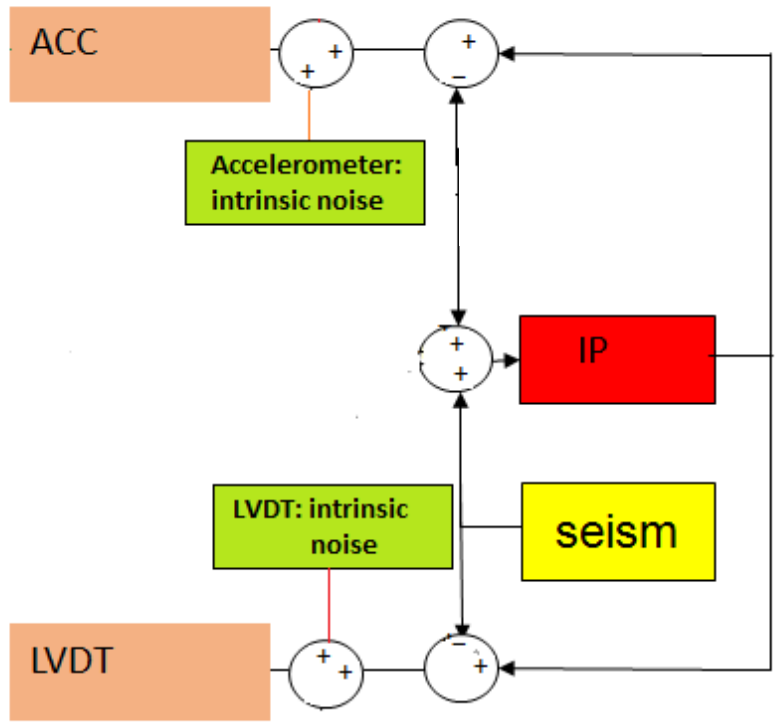
We want reduce the contribution of the seismic noise

⬇

Blending technique

Blending technique (I)

To take the better part of both signals, the *blended virtual sensing signals*, is attained through neutral pre-filtering.



ACC or GEO

High Pass filter (HP)

LVDT

Low Pass filter (LP)

HP+LP=1

- **LP filter must be shaped taking into account the background disturbance (seismic noise)**
- **For LP filter tipical cutoff is below 100 mHz, to reduce the seismic contribution.**
- **For HP filter we should be careful not to reintroduce accelerometer noise.**

Blended Sensor is defined as : $S(\omega) = LP(\omega) \cdot S_{LVDT}(\omega) - \omega^{-2} HP(\omega) \cdot S_{Acc}(\omega)$

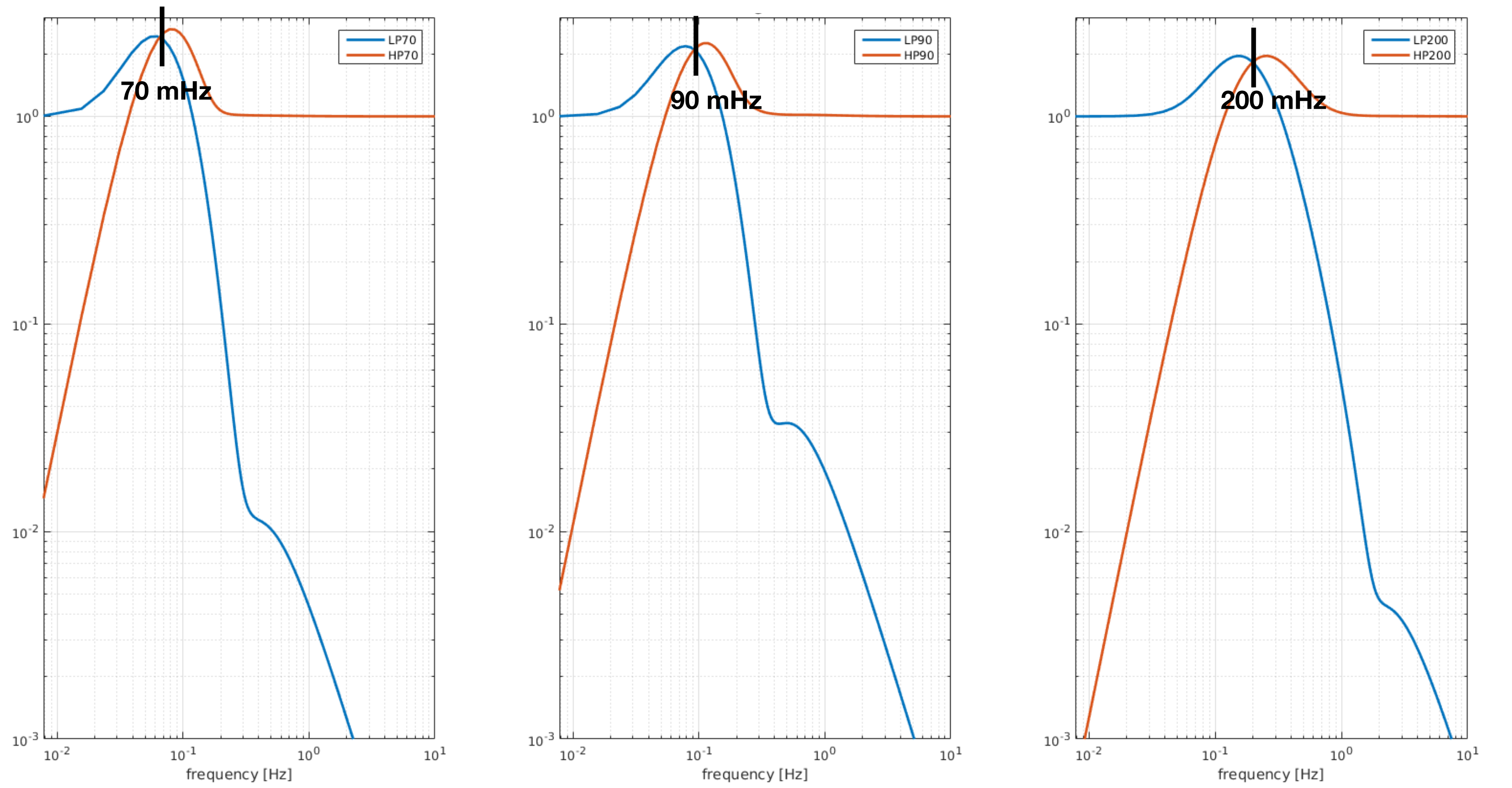
Blending technique (I)

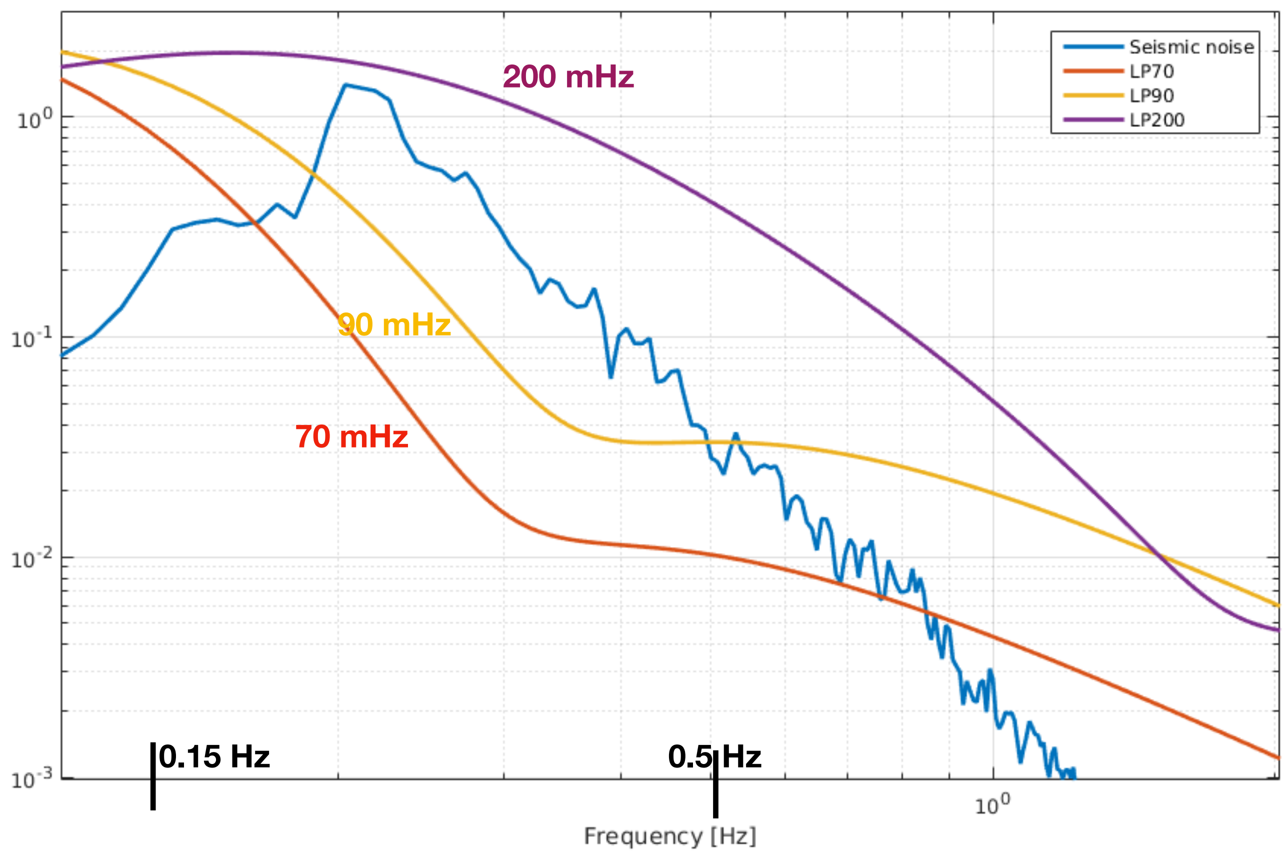
Example of blending filters:

✦**Blending frequency: 70 mHz**

✦**Blending frequency: 90 mHz**

✦**Blending frequency: 200 mHz**

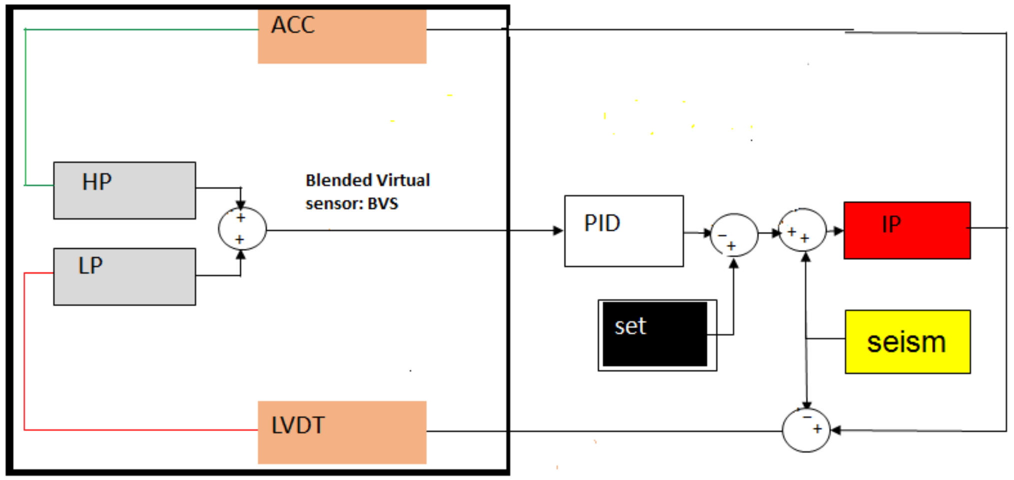




Impact of each one of these strategies on the seismic noise:

The 90 mHz and 70 mHz are shaped to reduce the re-injection of seismic noise in the range [0.2 -0.5] Hz

Inertial damping: IP residual motion

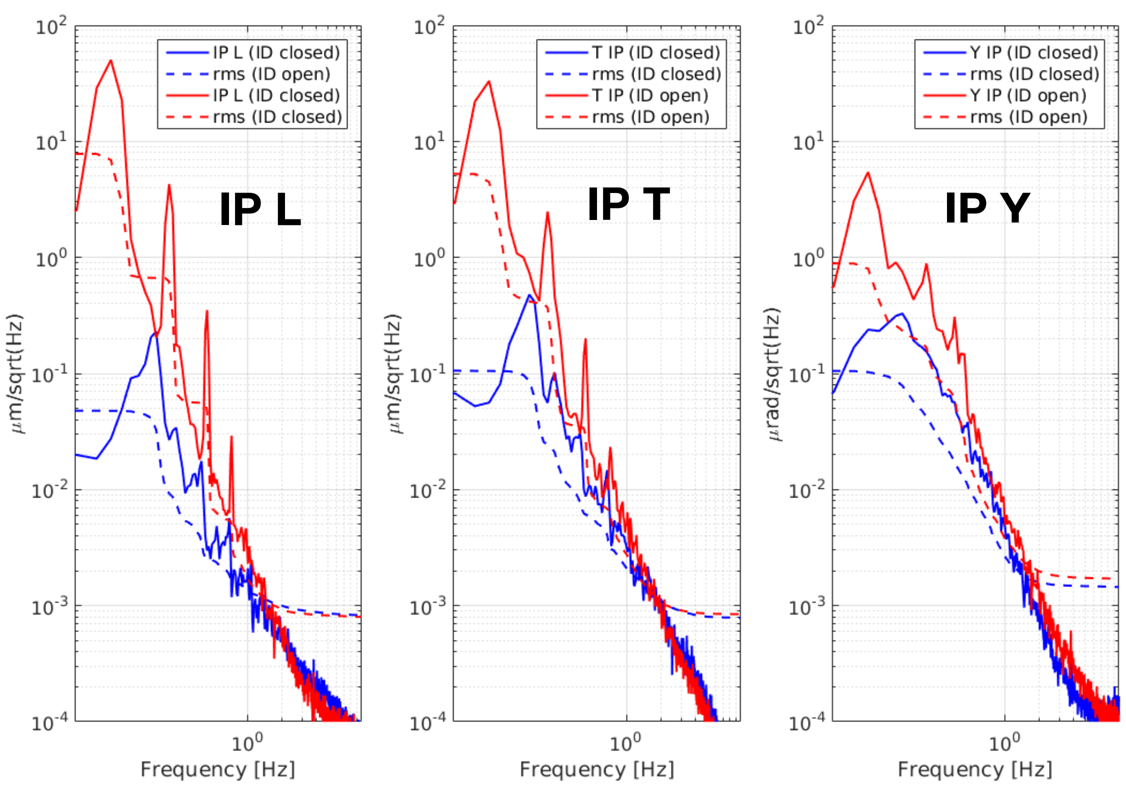


The closed loop signal is defined as

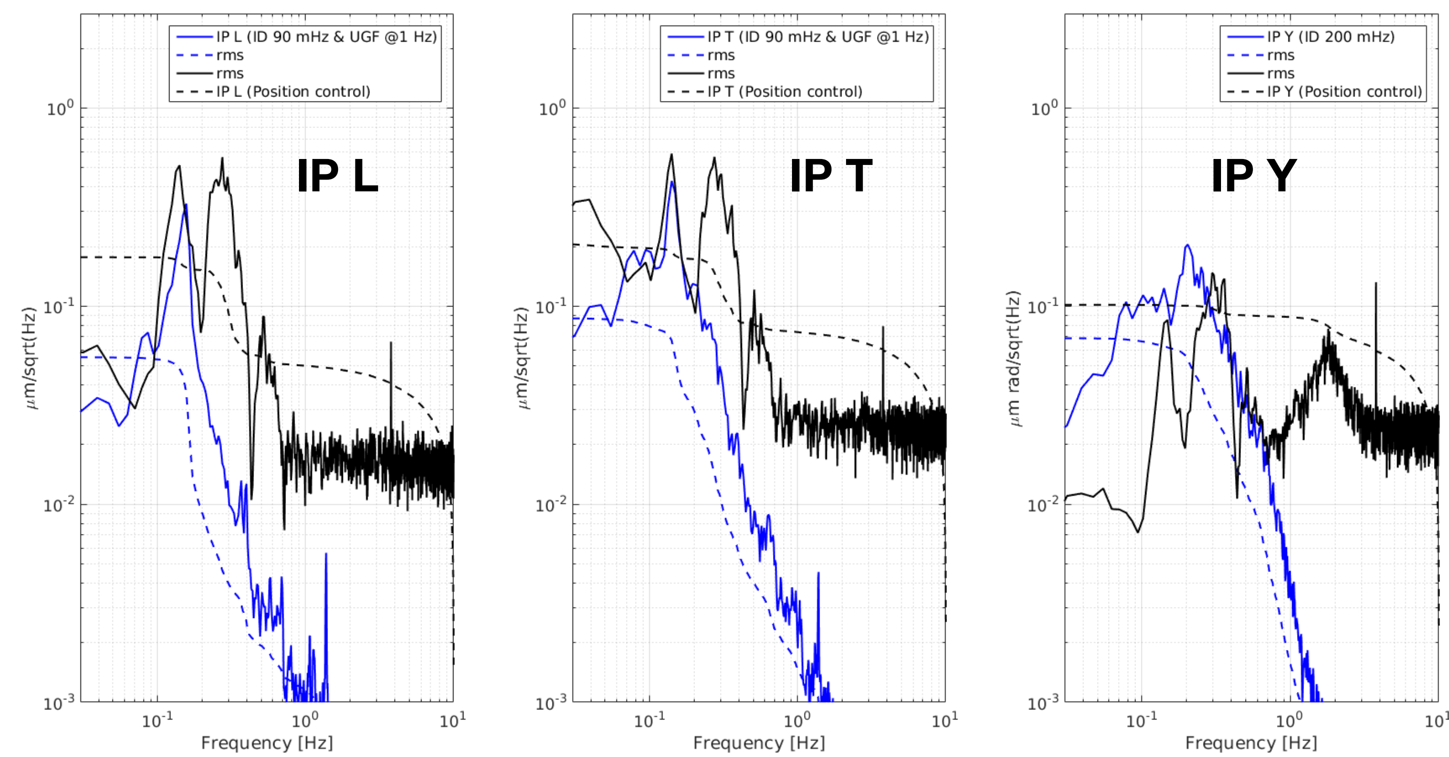
$$\tilde{S}_{iv}^{CL}(\omega) = \frac{\tilde{S}_{iv}(\omega)}{1 - \tilde{M}_i(\omega) \cdot \tilde{C}_i(\omega)}$$

IP blended signal = Error signal in L, T ,Y

In this configuration the residual motion of the IP is



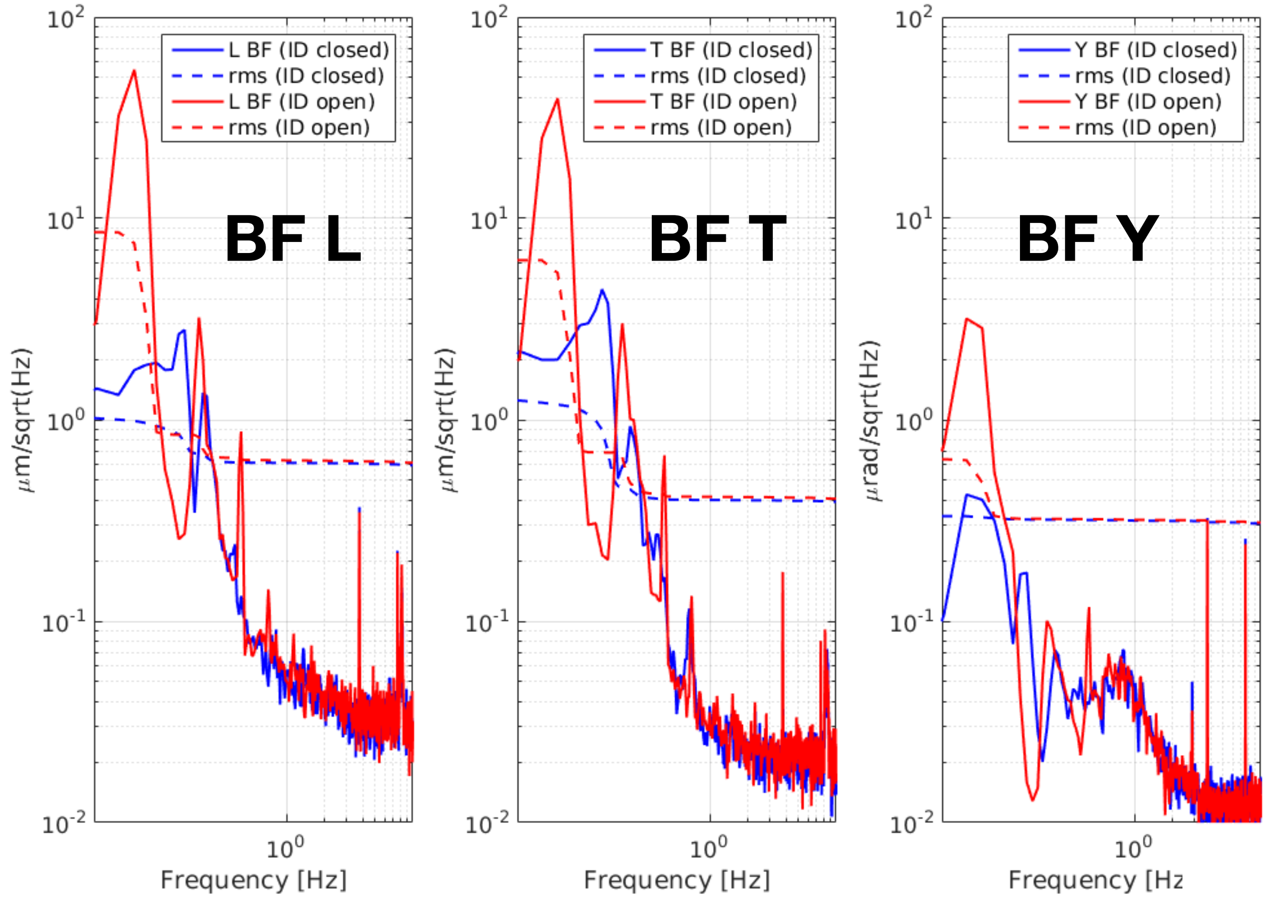
Open loop versus closed loop with Inertial Damping



Closed loop: LVDT is the error signal

Closed loop: blended signal is the error signal

Inertial damping: BF & Test Mass (TM) residual motion

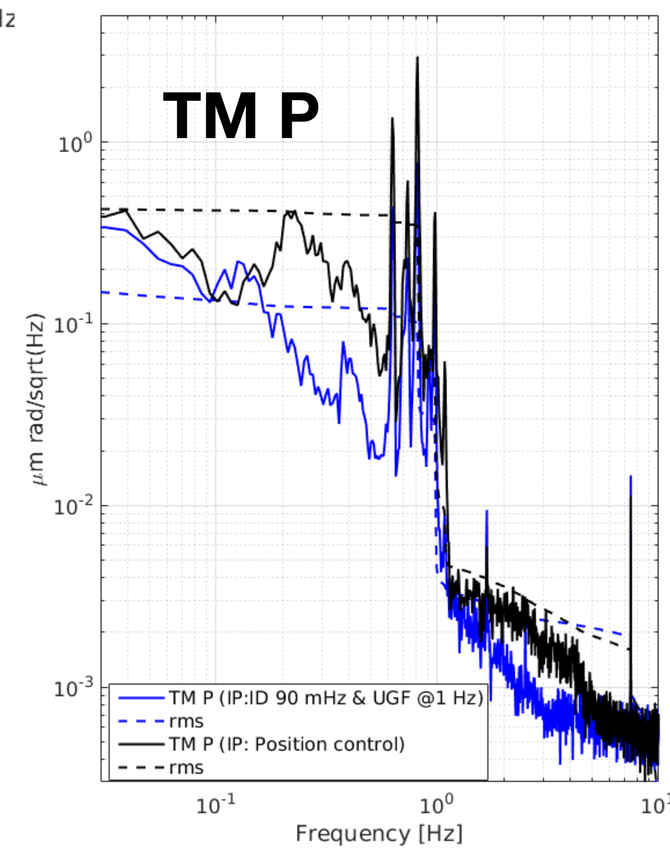


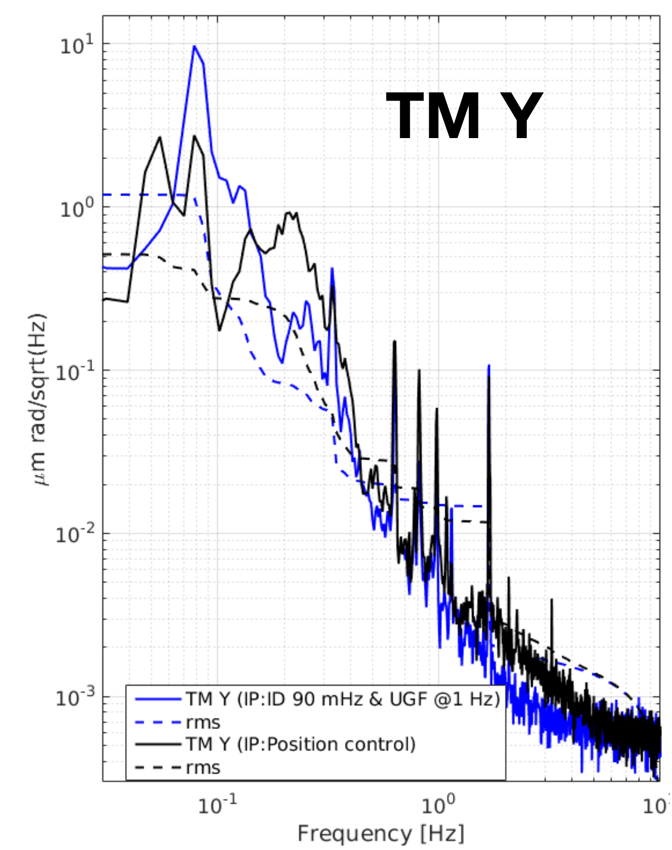
In this configuration:

- ✦ BF L: damp off
- ✦ BF T: damp off
- ✦ BF Y: damp on

In this configuration:

- ✦ MN & TM P: damp off
- ✦ MN & TM Y: damp off





Conclusion and next steps

- We have diagonalized sensors and actuators
- We applied the bending technique to ITMX
  - L and T blending frequency: 90 mHz
  - Yaw blending frequency: 200 mHz
- Thanks to the implementation of the inertial damping we observed a reduced motion of IP, BF and TM

	L RMS [μm]	T RMS [μm]	Y RMS [μrad]	P RMS [μrad]
IP	0,05	0,08	0,08	
BF	1	1	0,3	
TM			1	0,2

- **IP inertial damping ON**
- **YAW BF damping ON**
- **All other d.o.f NOT DAMPED**

- The test on ITMX shows that inertial damping (ID) reduces the test mass motion more than the position control with only LVDTs
- We need to implement the ID on all the type A suspension also by using the geophone.

Thanks for your attention!