Type A control: inertial damping performances

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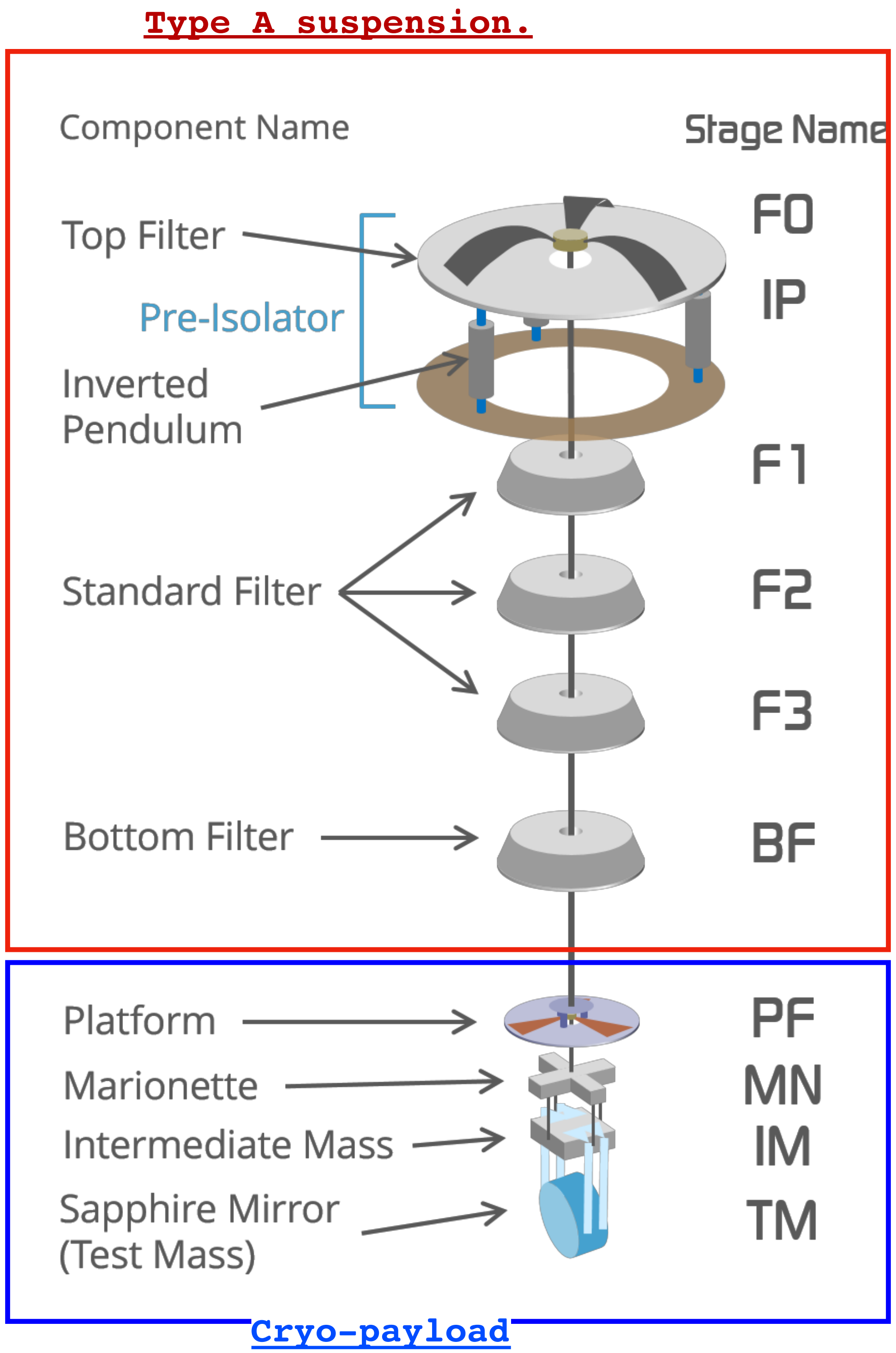
OUTLINE

- Introduction
- Sensor diagonalization
- Transfer functions
- Inertial sensors
- Noise budget of diagonalized sensors
- Blending technique
- Inertial damping: ITMX results
- Conclusion

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 2 Hz)

Introduction

- 14 position sensors (LVDT)
- 3 inertial sensors (Accelerometer or geophone) →
- OSEM, optical levers, 26 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:

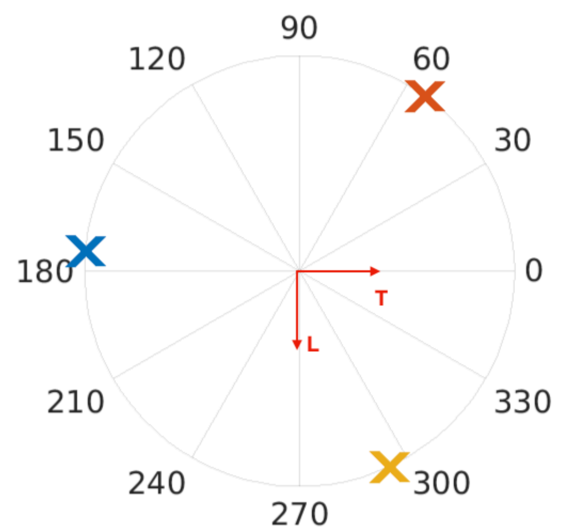
- On the IP is implemented an Active Mode Damping of the resonance modes and for seismic noise reduction
- On the BF and on the GAS filters a viscous damping control of the resonance modes is implemented

Sensors diagonalization (I)

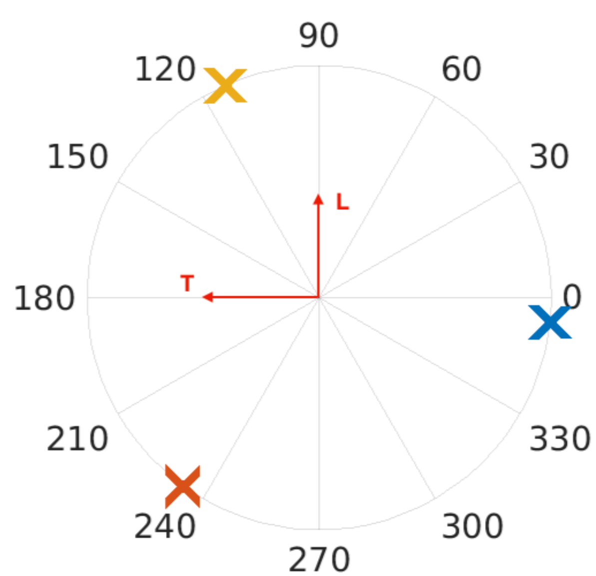
To implement the Damping control on the IP and on the BF first we build the diagonalized sensors and actuators in the (L,T,Y) base

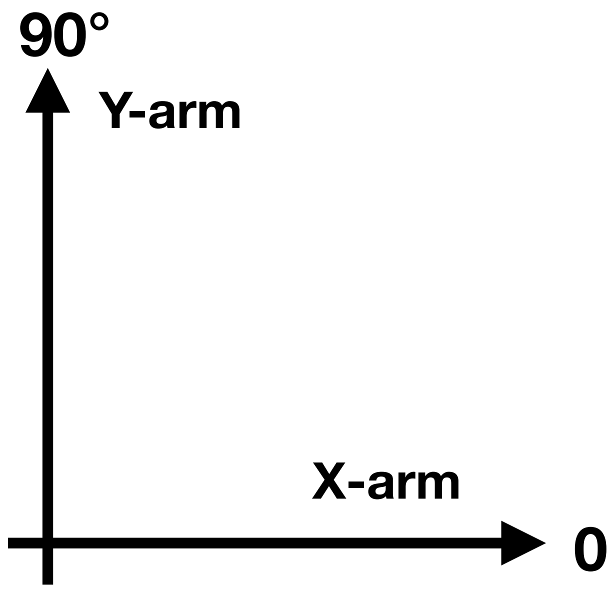
IP LVDTs arrangement

Y End

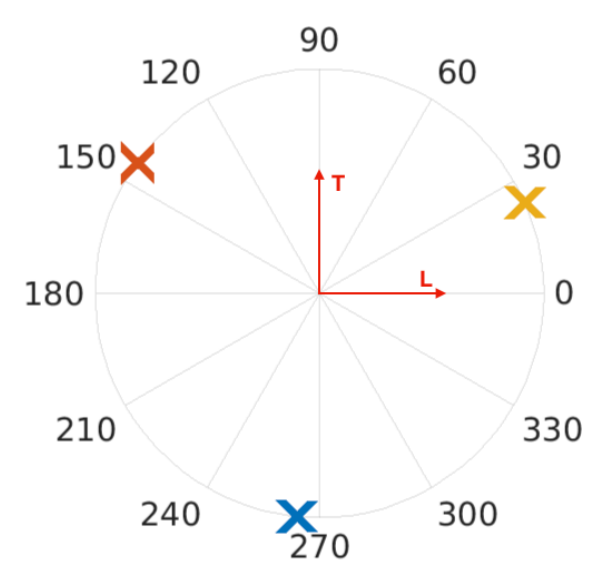


Y Front

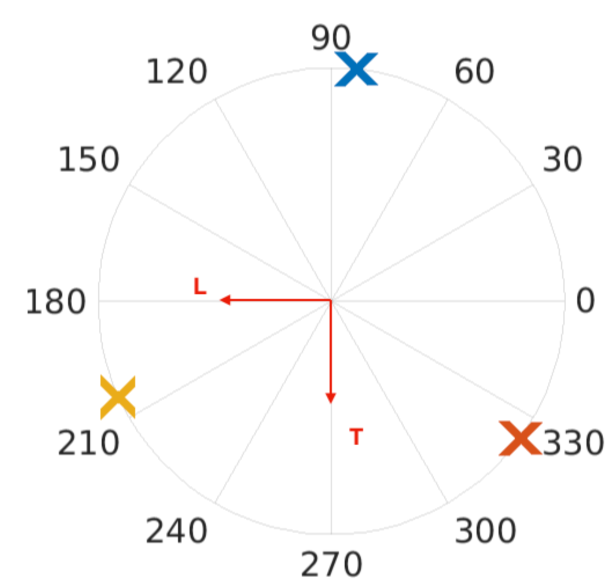




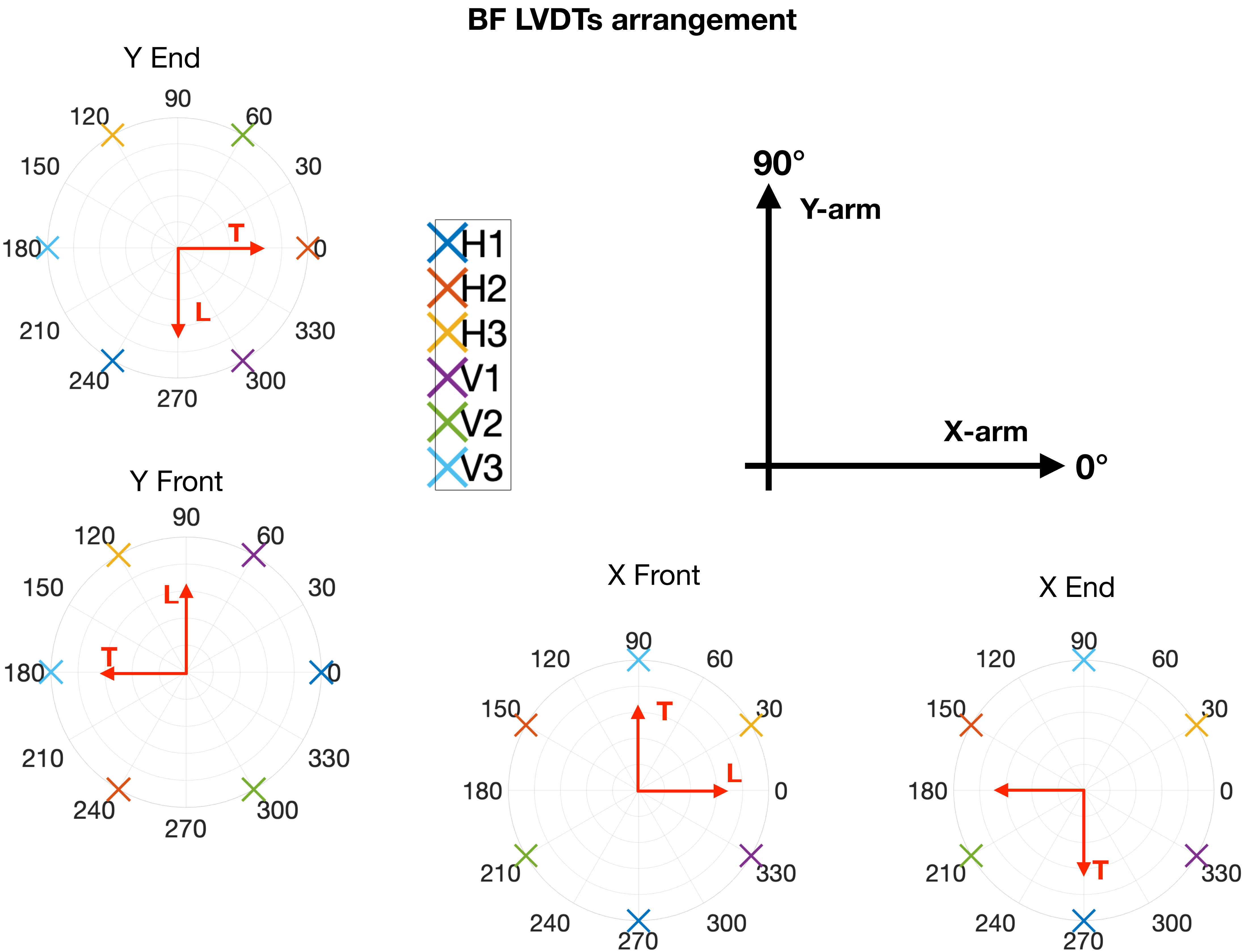
X Front



X End



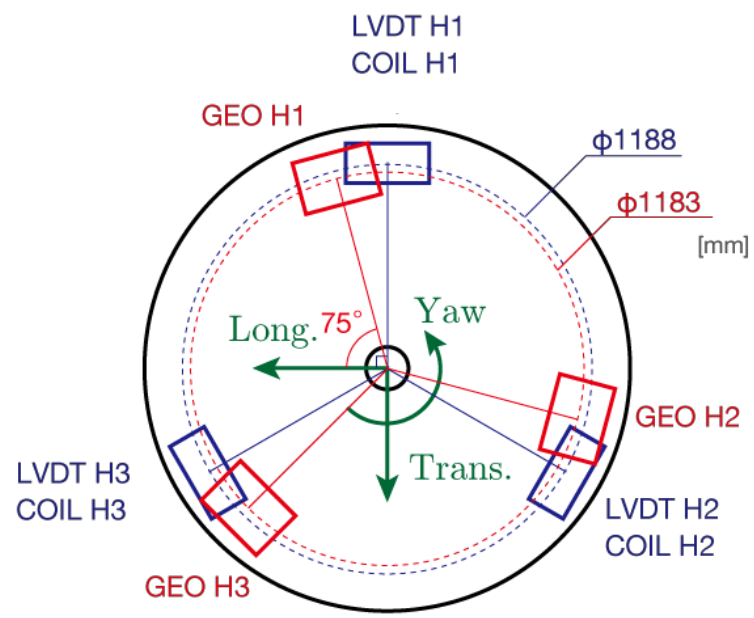
Sensors diagonalization (II)



Sensors diagonalization (III)

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



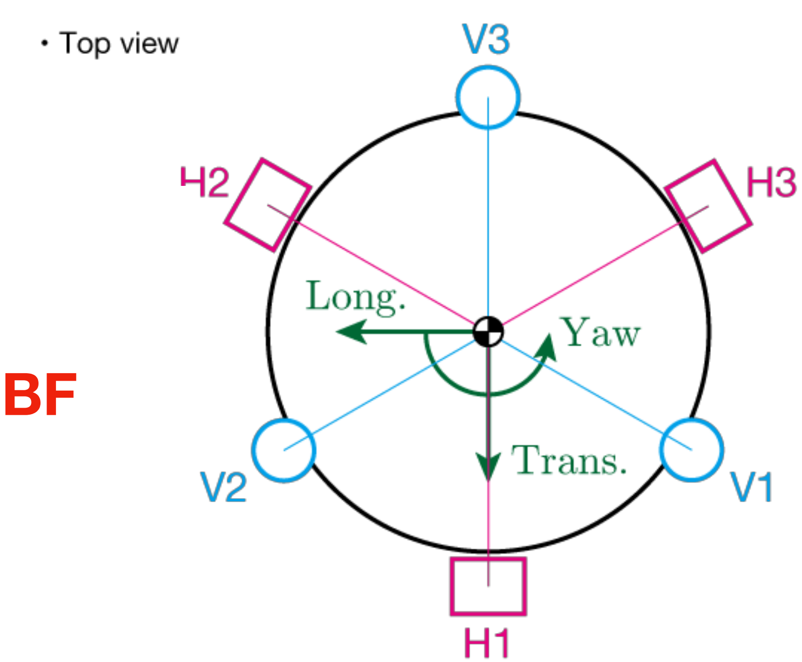
LVDTs sensing matrix

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

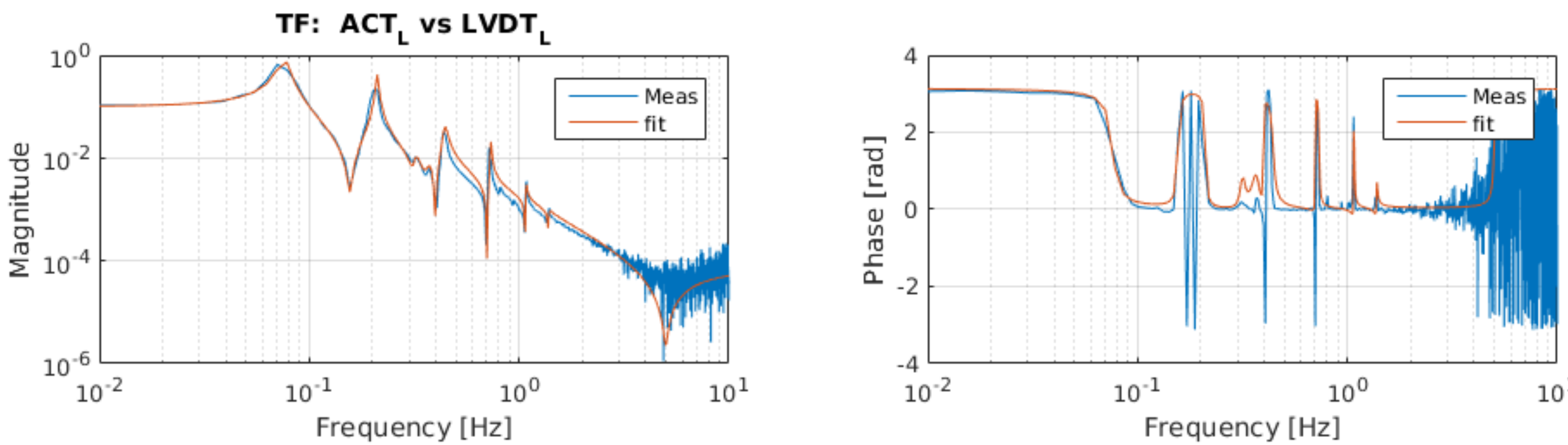
sensor base: (H1, H2,H3) (V1, V2,V3) — *Geometrical transformation* → **Euler base: (L, T,Y) (P, R,V)**

Driving matrix

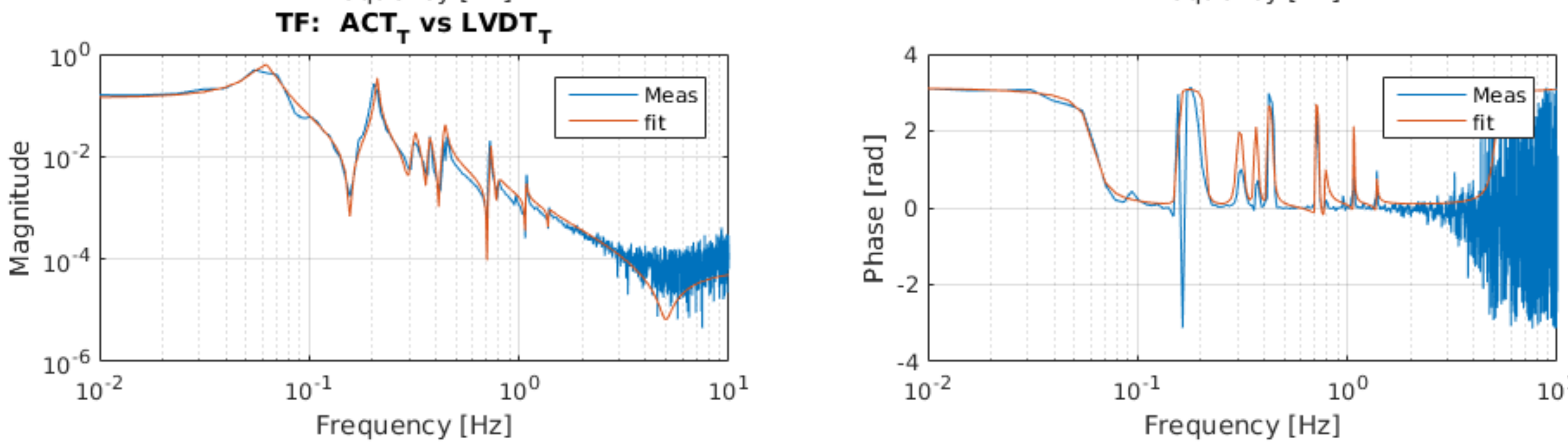
Actuators base: (H1, H2,H3) (V1, V2,V3) — *Geometrical transformation* → **Euler base: (L, T,Y) (P, R,V)**

IP mechanical transfer functions

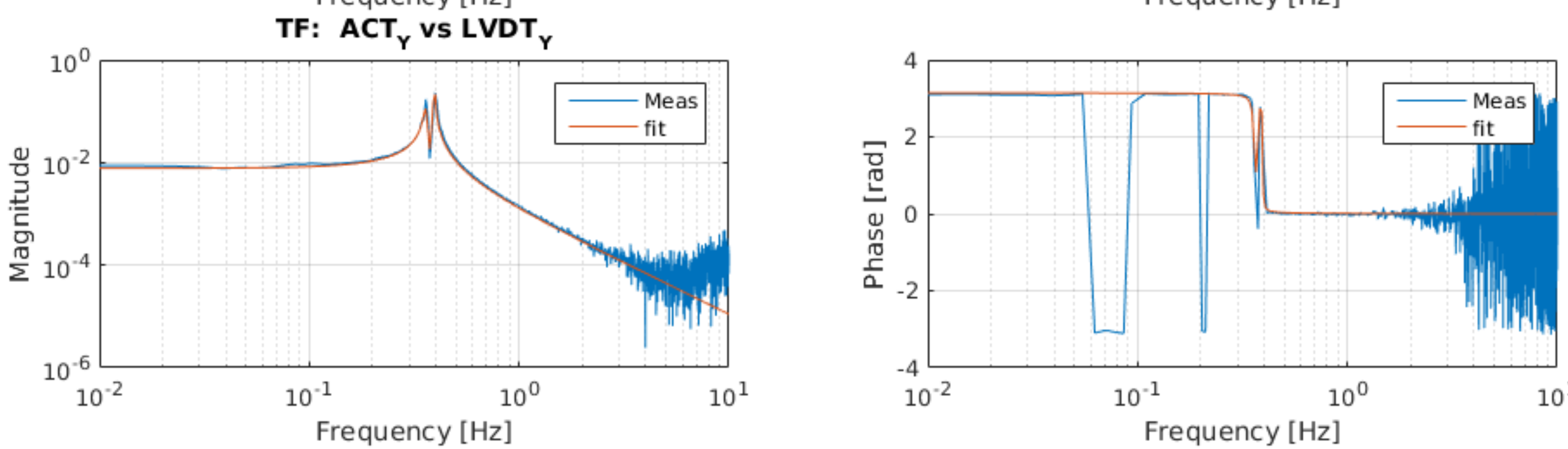
IP: L



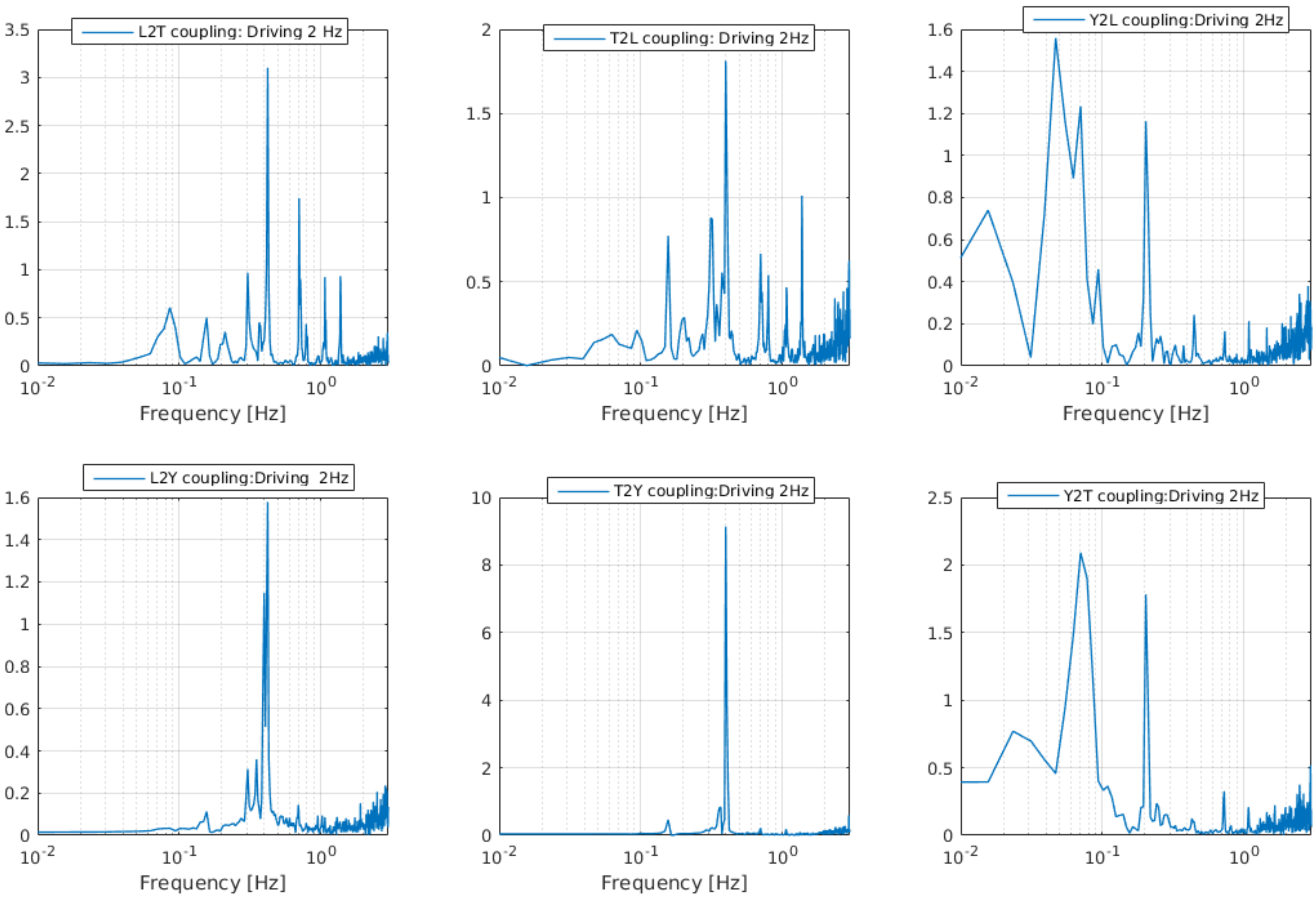
IP:T



IP:Y

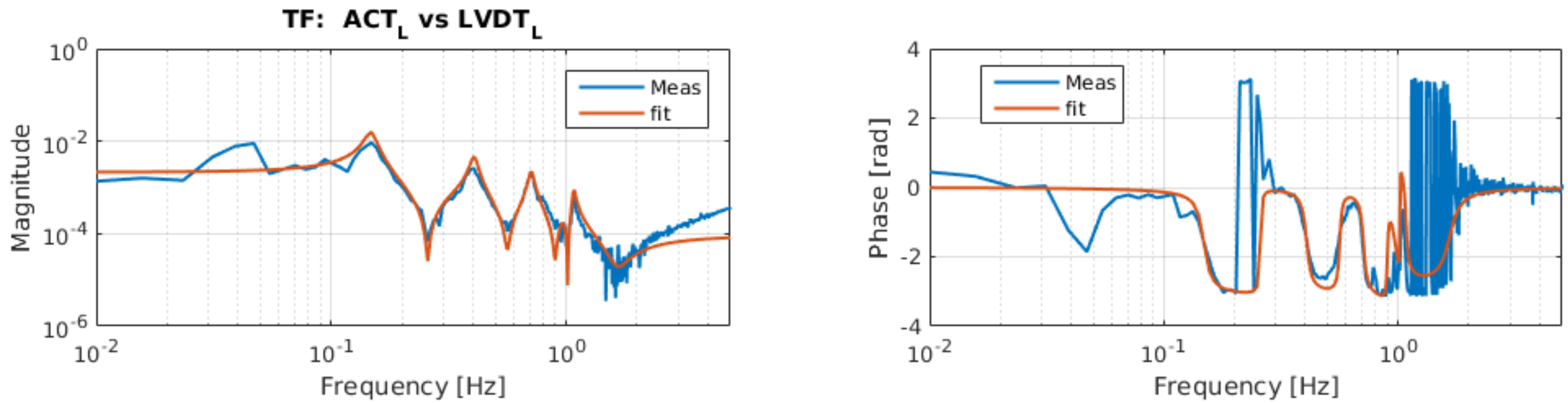


IP mechanical residual couplings after actuator diagonalization

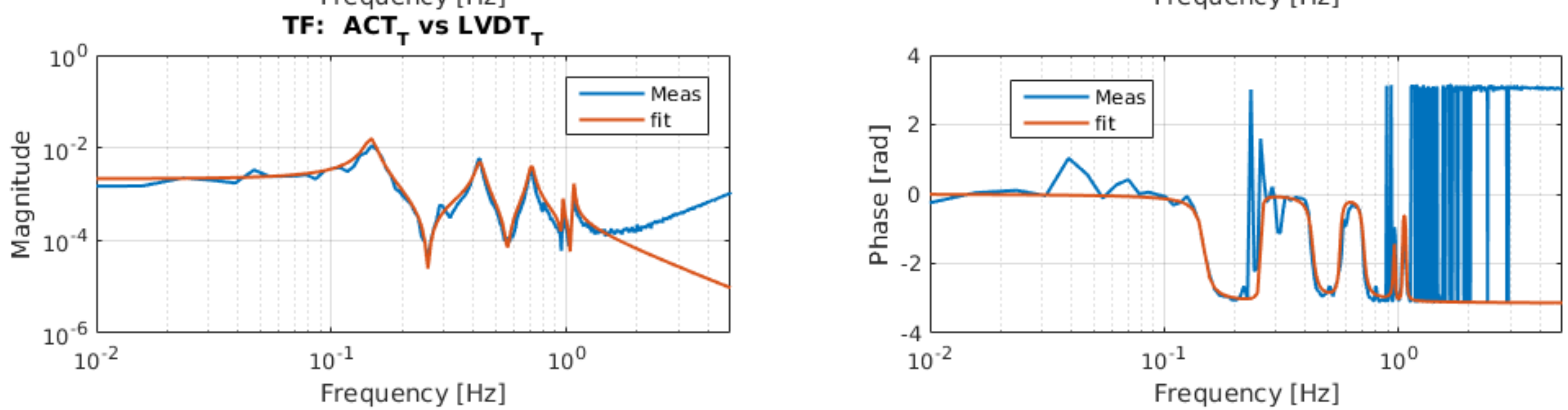


Bottom Filter mechanical transfer functions (I)

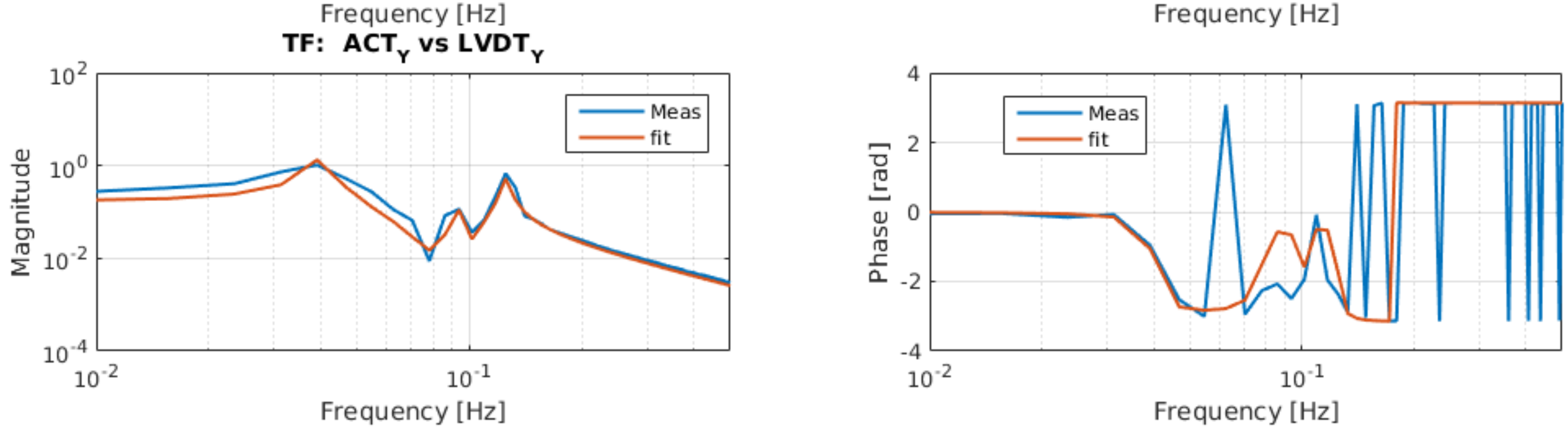
BF: L



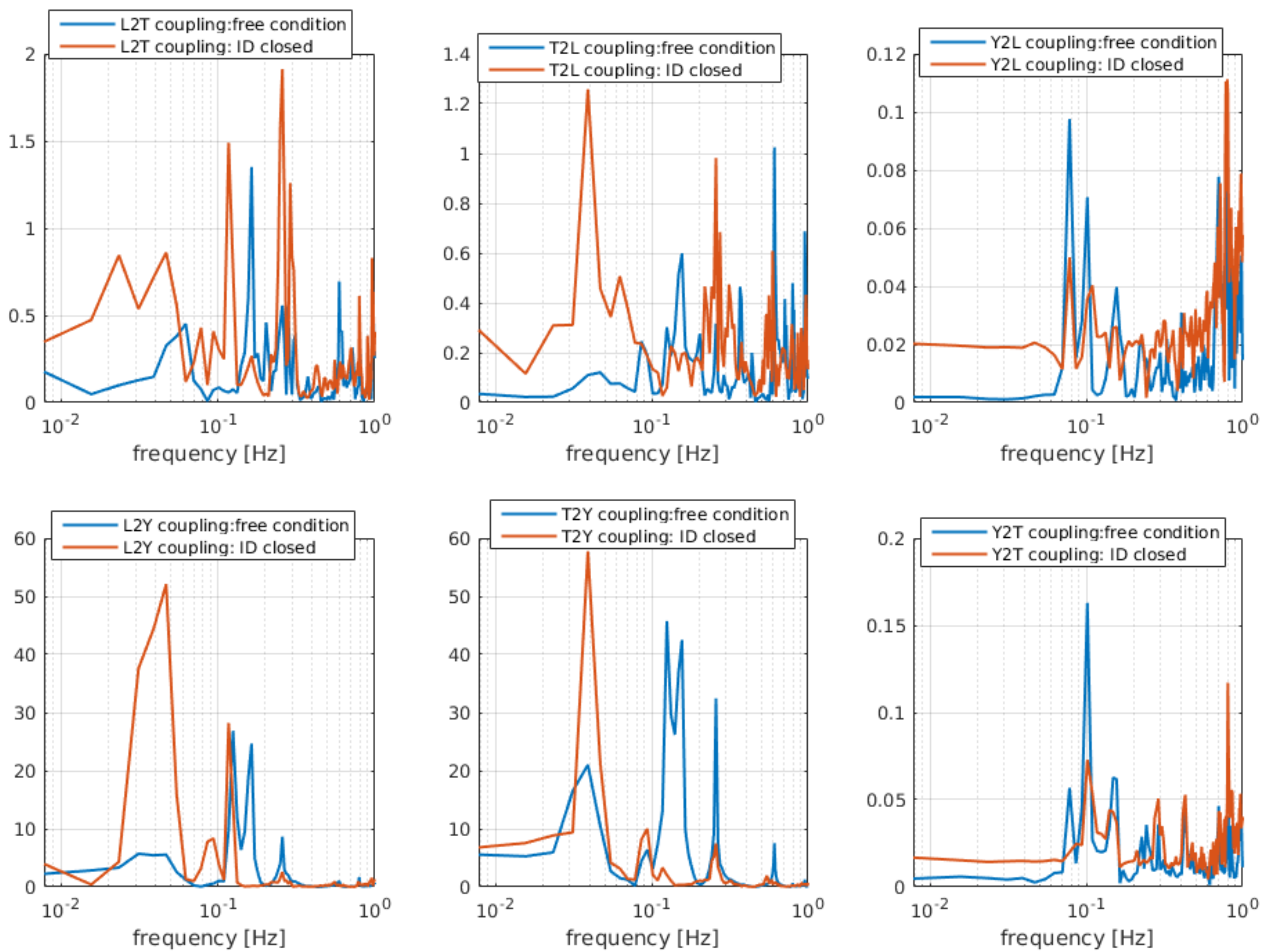
BF: T



BF: Y

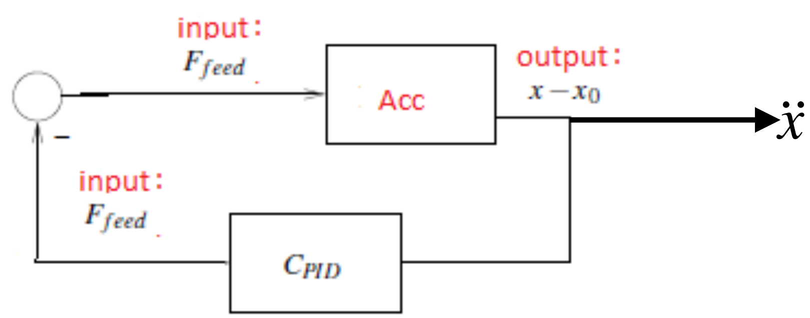


BF mechanical residual couplings after actuator diagonalization



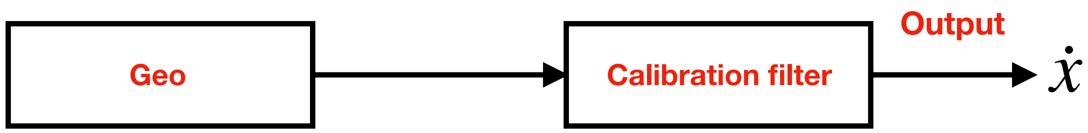
Inertial sensor (I)

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!

One way to do this calibration is inject white noise along the IP Yaw degree of freedom and to measure the transfer function:

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

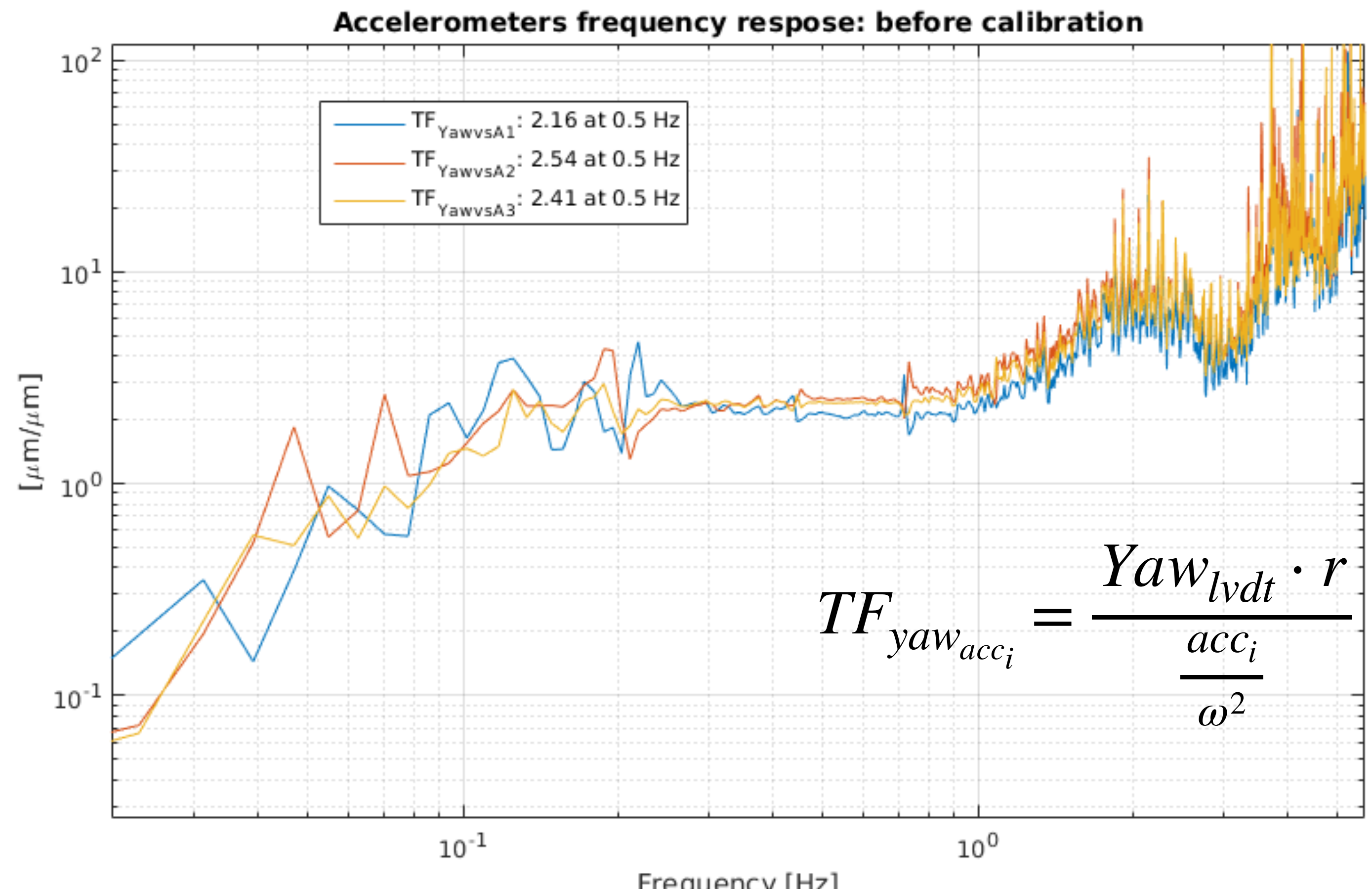
$$TF_{yaw_{geo_i}} = \frac{Yaw_{lvdt} \cdot r}{\frac{geo_i}{\omega}}$$

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

Since the Yaw is an isotropic motion we expect that these TFs should be equals. If this happens the sensors are calibrated, otherwise we have to calibrate them.

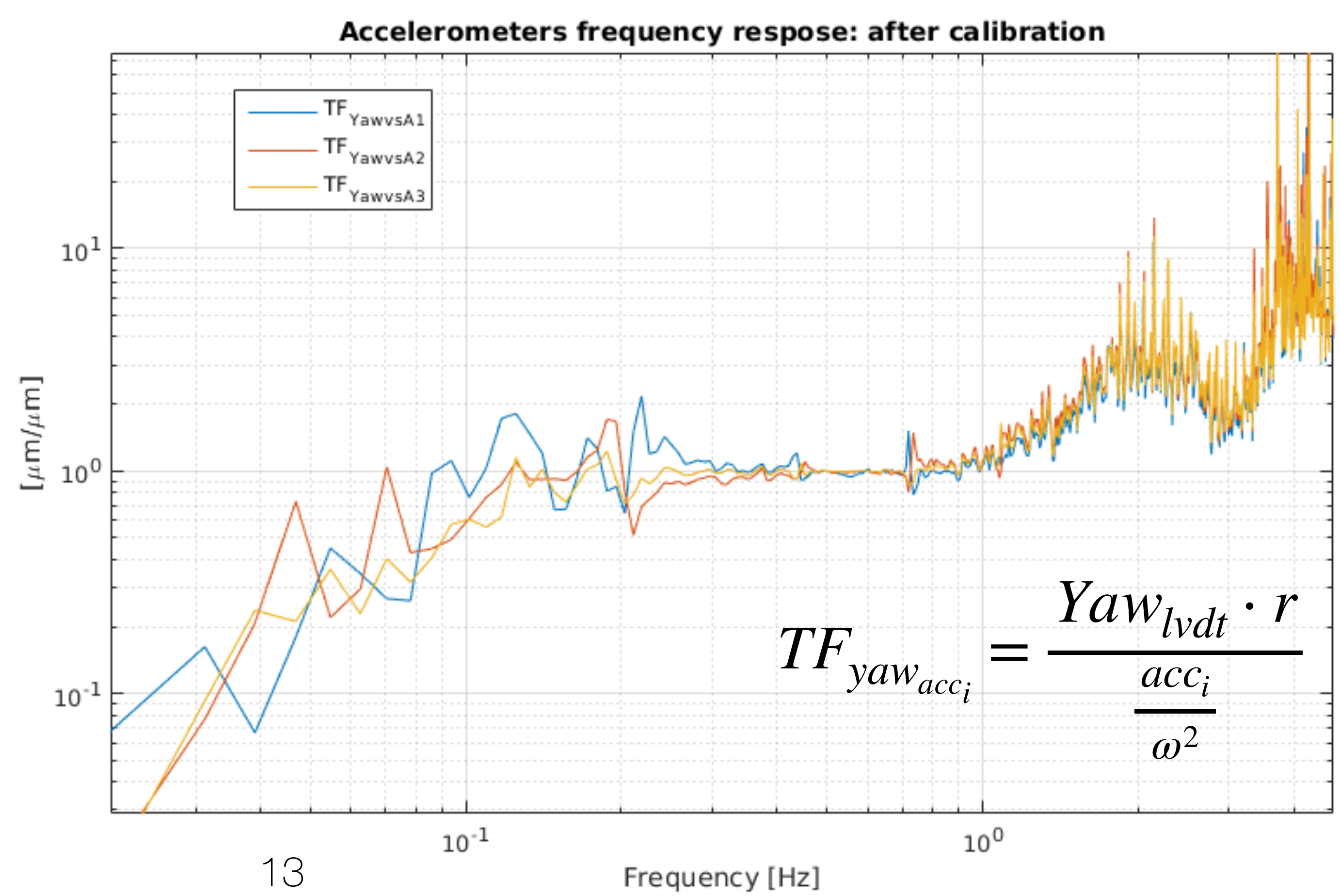
Inertial sensor (II)

Accelerometer response:
Before calibration



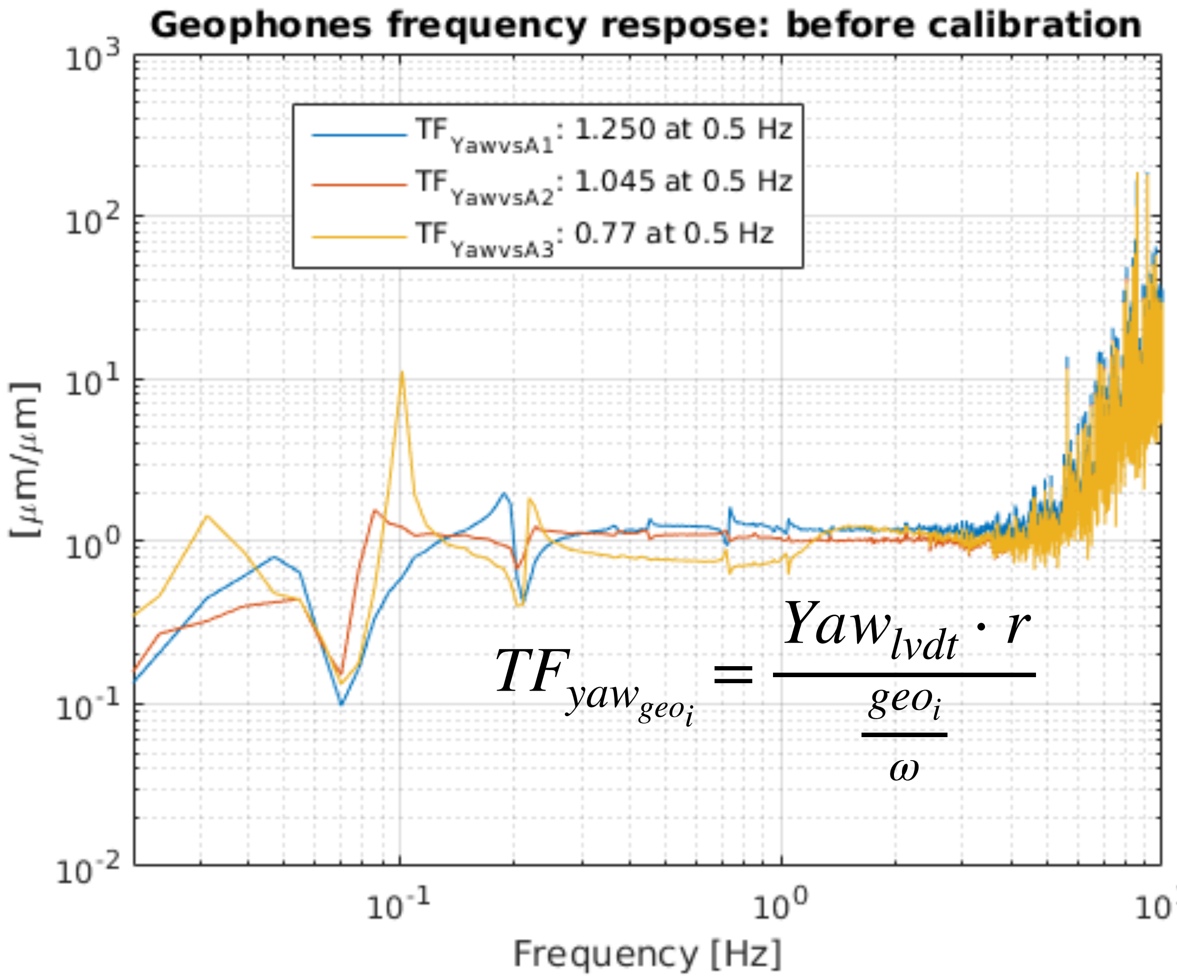
$$TF_{yaw_{acc_i}} = \frac{Yaw_{lvdt} \cdot r}{\frac{acc_i}{\omega^2}}$$

Accelerometer response:
After calibration



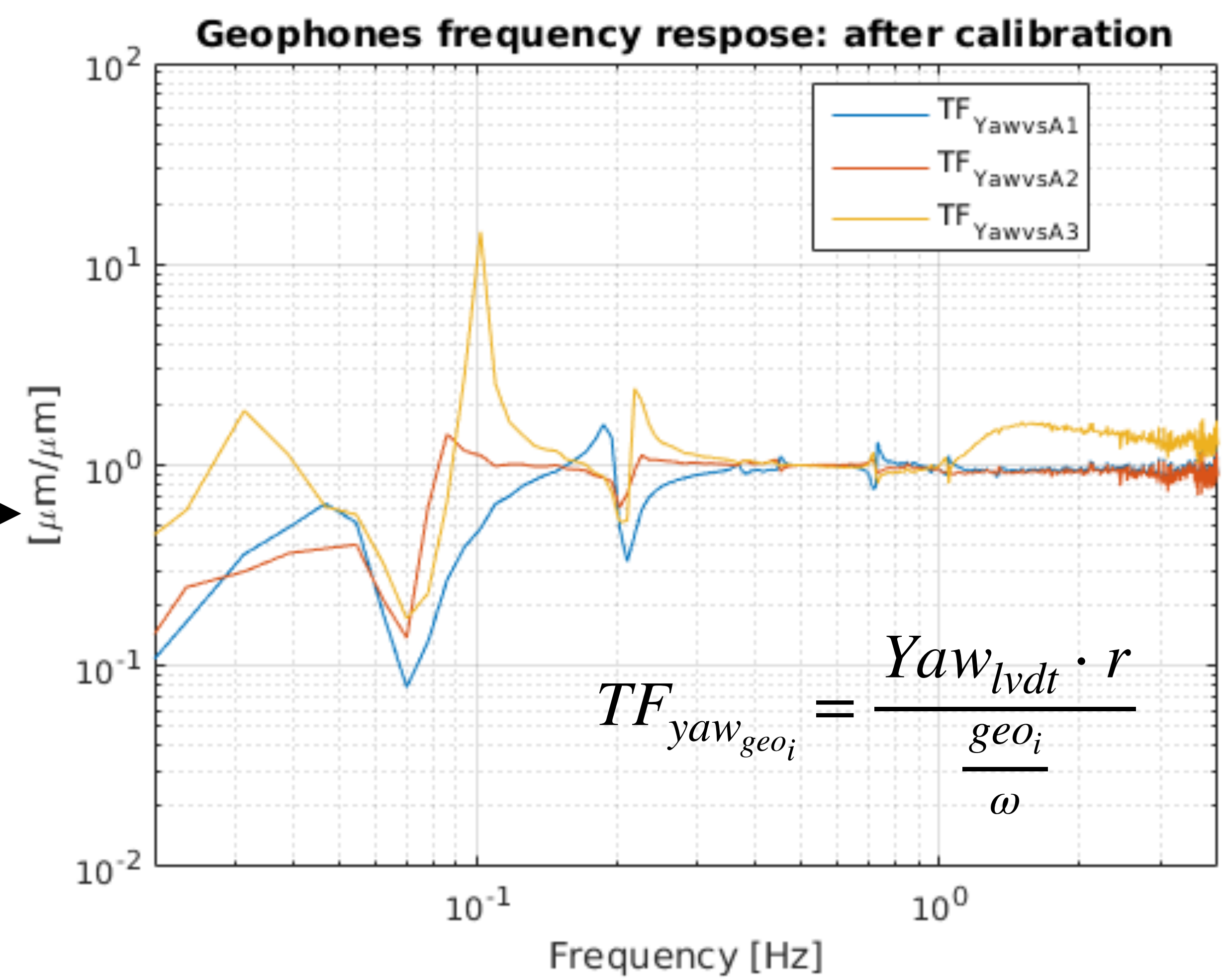
$$TF_{yaw_{acc_i}} = \frac{Yaw_{lvdt} \cdot r}{\frac{acc_i}{\omega^2}}$$

Inertial sensor (III)



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

Geophone response:
Before calibration

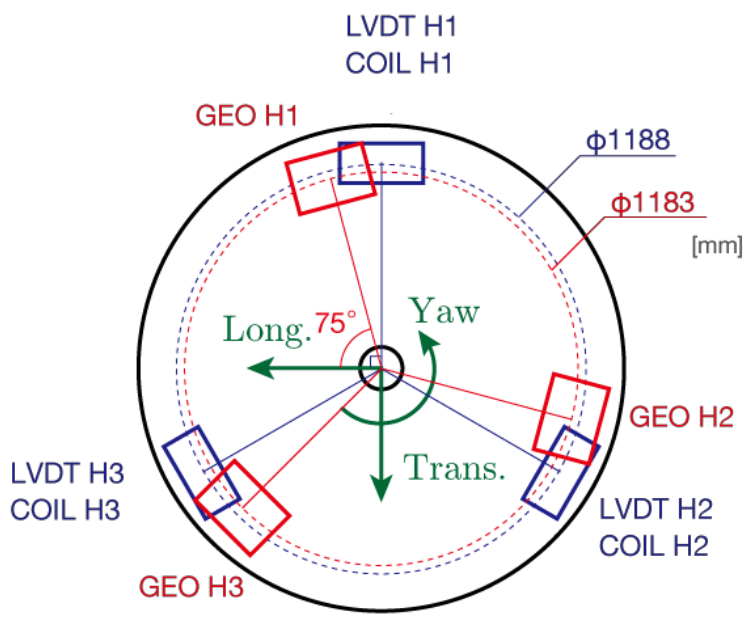


$$TF_{yaw_{geo_i}} = \frac{Yaw_{lvdt} \cdot r}{\frac{geo_i}{\omega}}$$

Geophone response:
After calibration

Inertial sensor diagonalization(I)

After that 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)**

We inject a line at 2Hz from each diagonalized actuator and we look at the TF:

Accelerometer

$$TF_{f_0=2Hz} = \frac{\left(\frac{Acc_j}{Lvdt_i}\right)}{\omega_0^2}$$

where i=L,T , Y ; j=1,2,3

Geophone

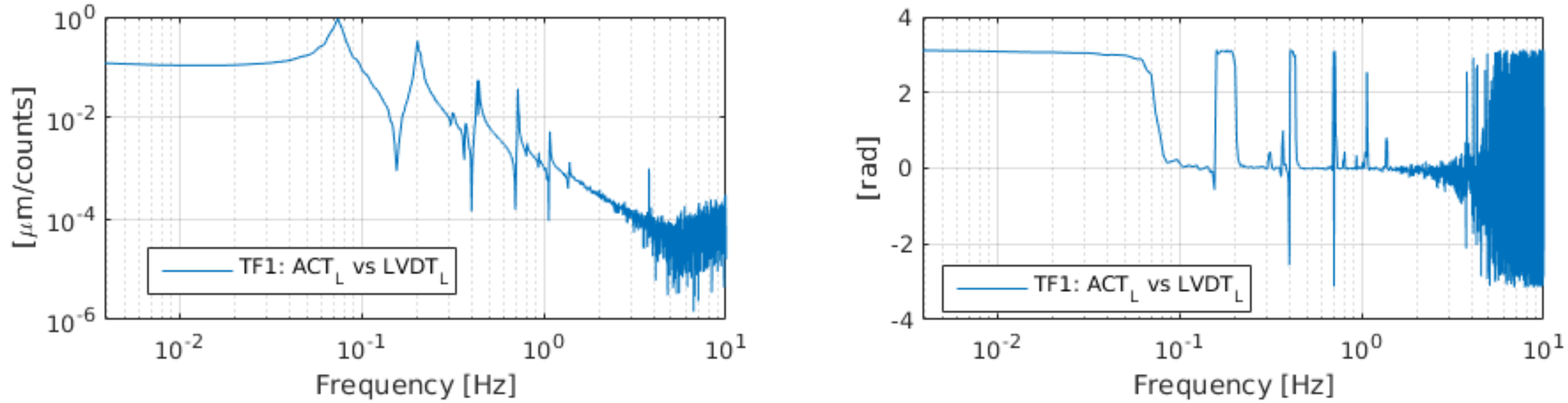
$$TF_{f_0=2Hz} = \frac{\left(\frac{Geo_j}{Lvdt_i}\right)}{\omega_0}$$

We measure the amplitude of the response (module) and the sign (phase) that each inertial sensor has when we move only along the selected degree of freedom

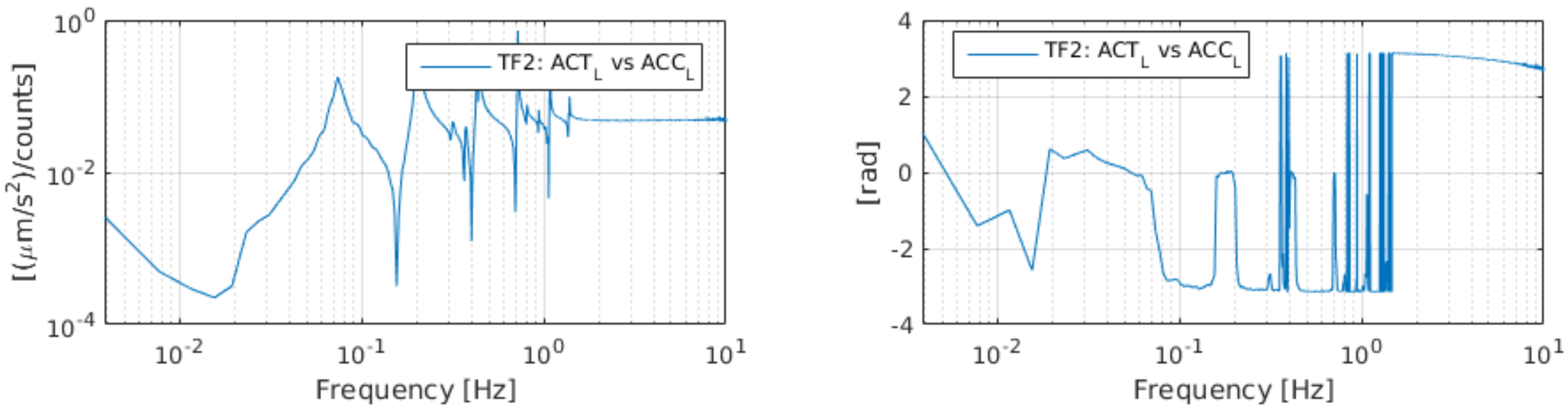
Inertial sensor: transfer functions (I)

TFs are the same: inter calibration and diagonalization working!

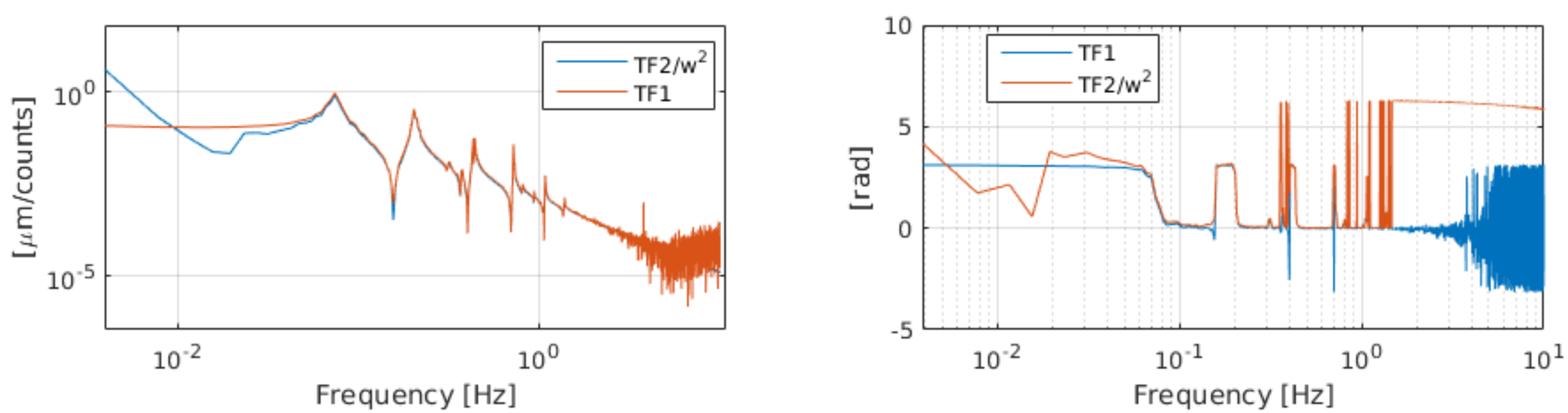
LVDT: L



ACC: L



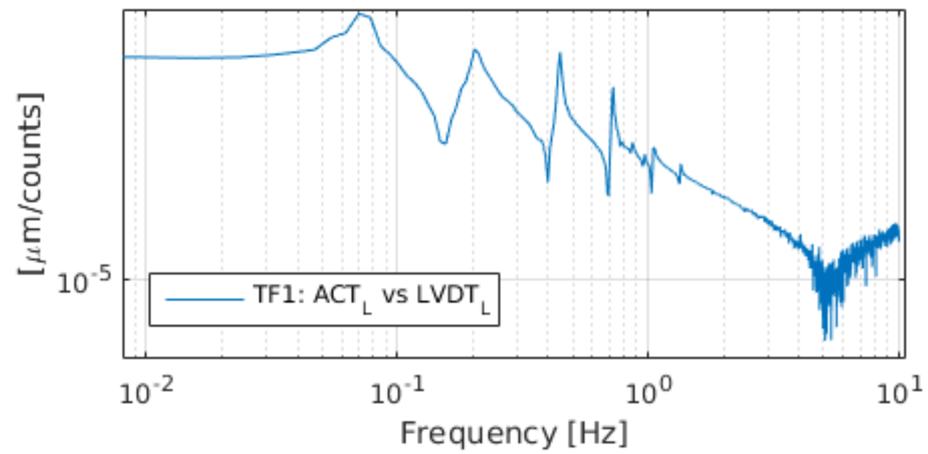
ACC & LVDT: L

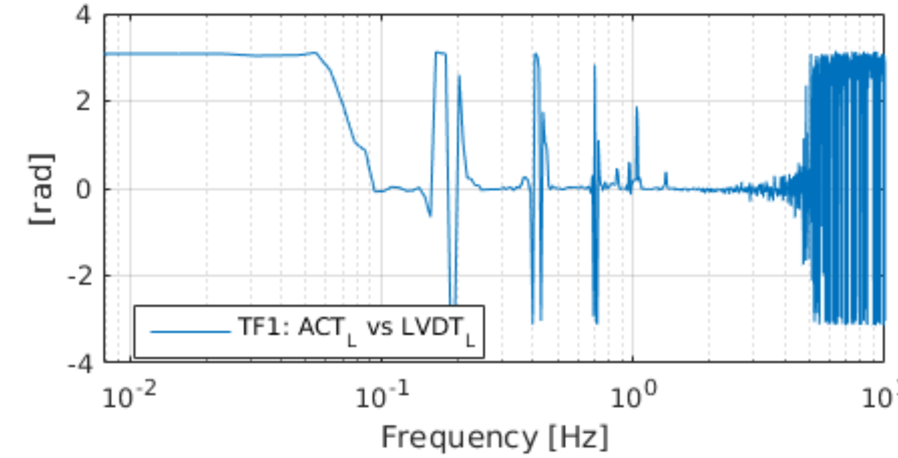


Inertial sensor: transfer functions (II)

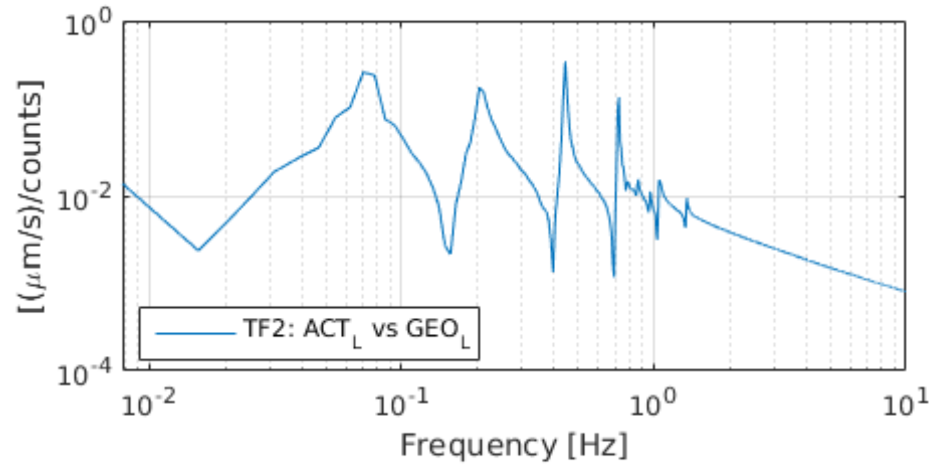
TFs are the same: inter calibration and diagonalization working!

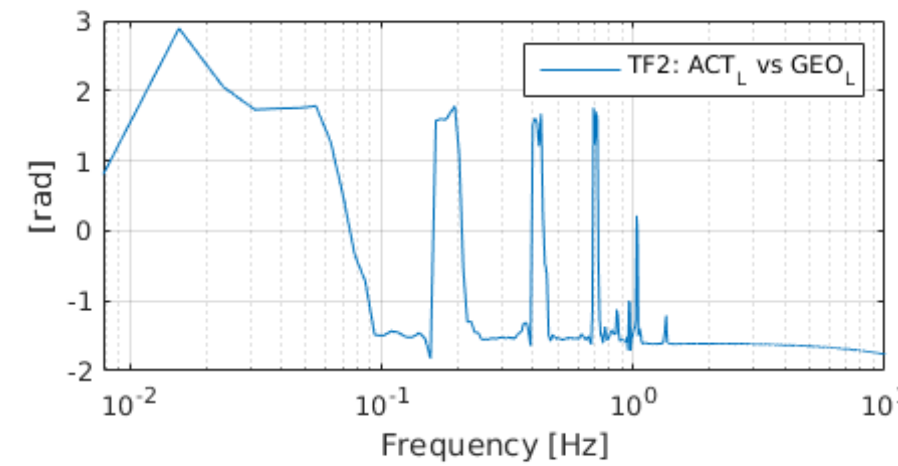
LVDT: L



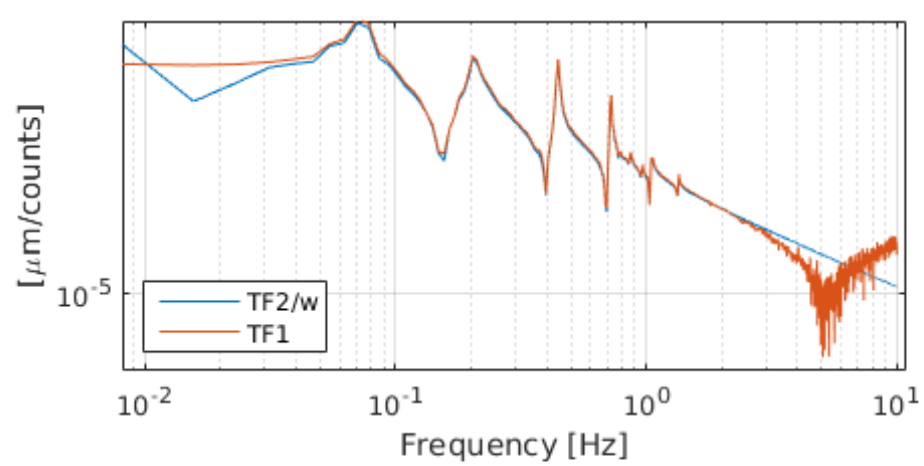


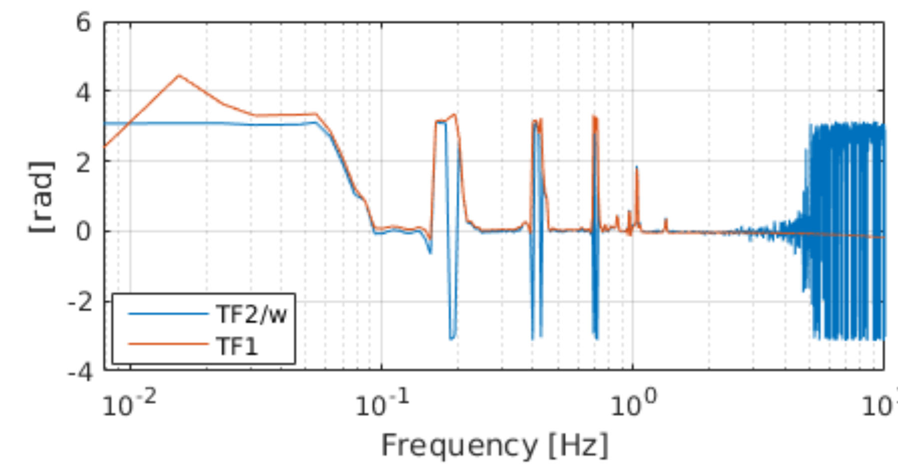
GEO: L





GEO & LVDT: L

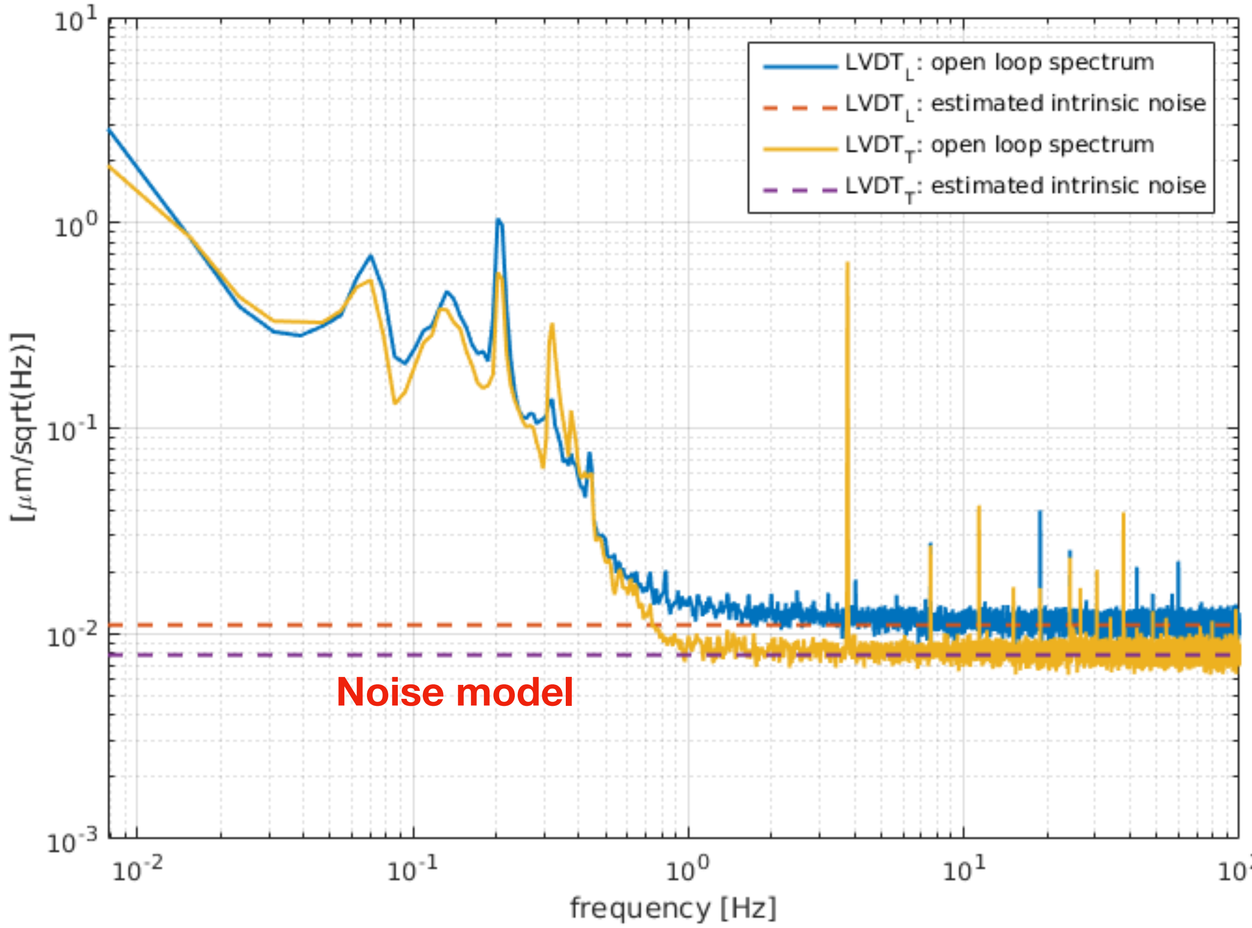




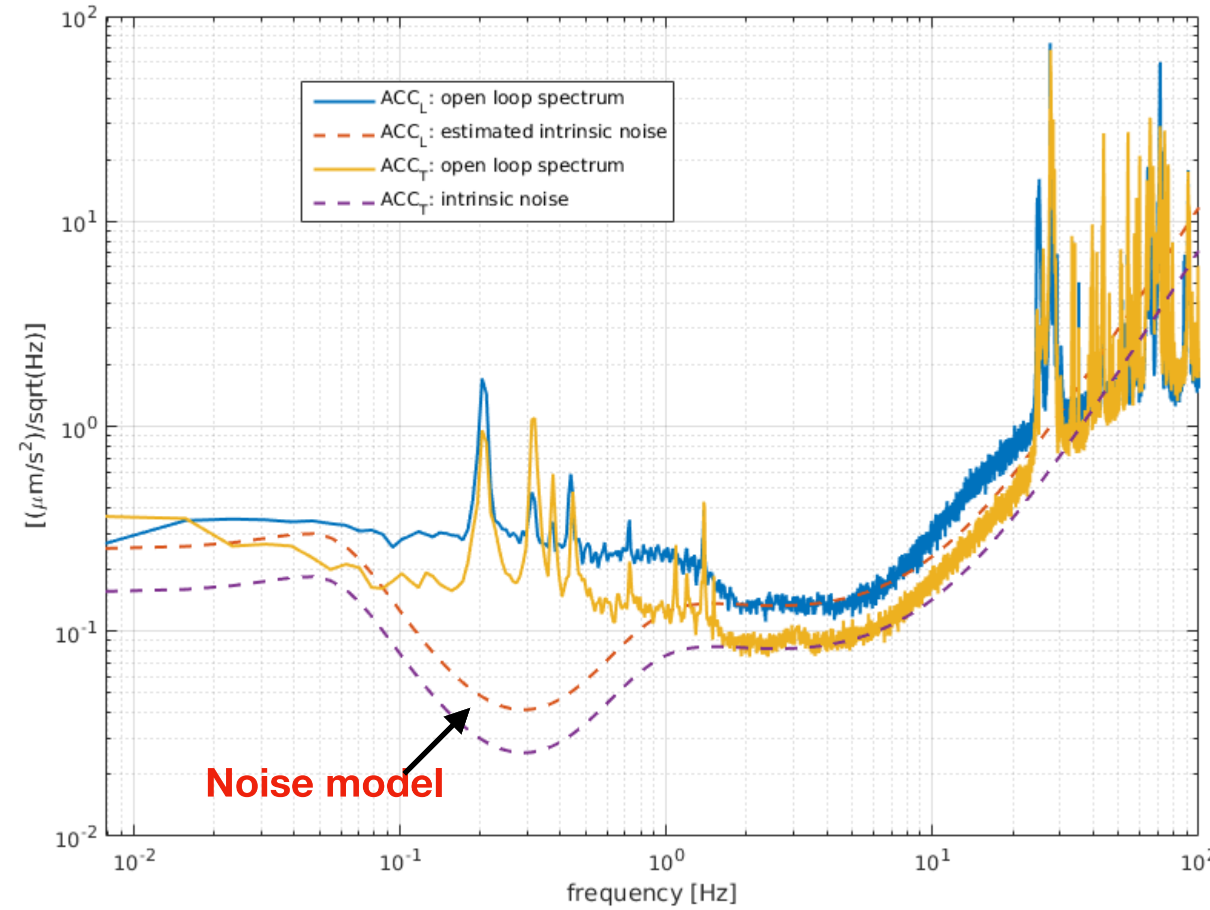
Noise budget of diagonalized sensors (I)

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

ITMX LVDT



ITMX ACC



LVDT spectrum signal

Versus intrinsic noise (model)

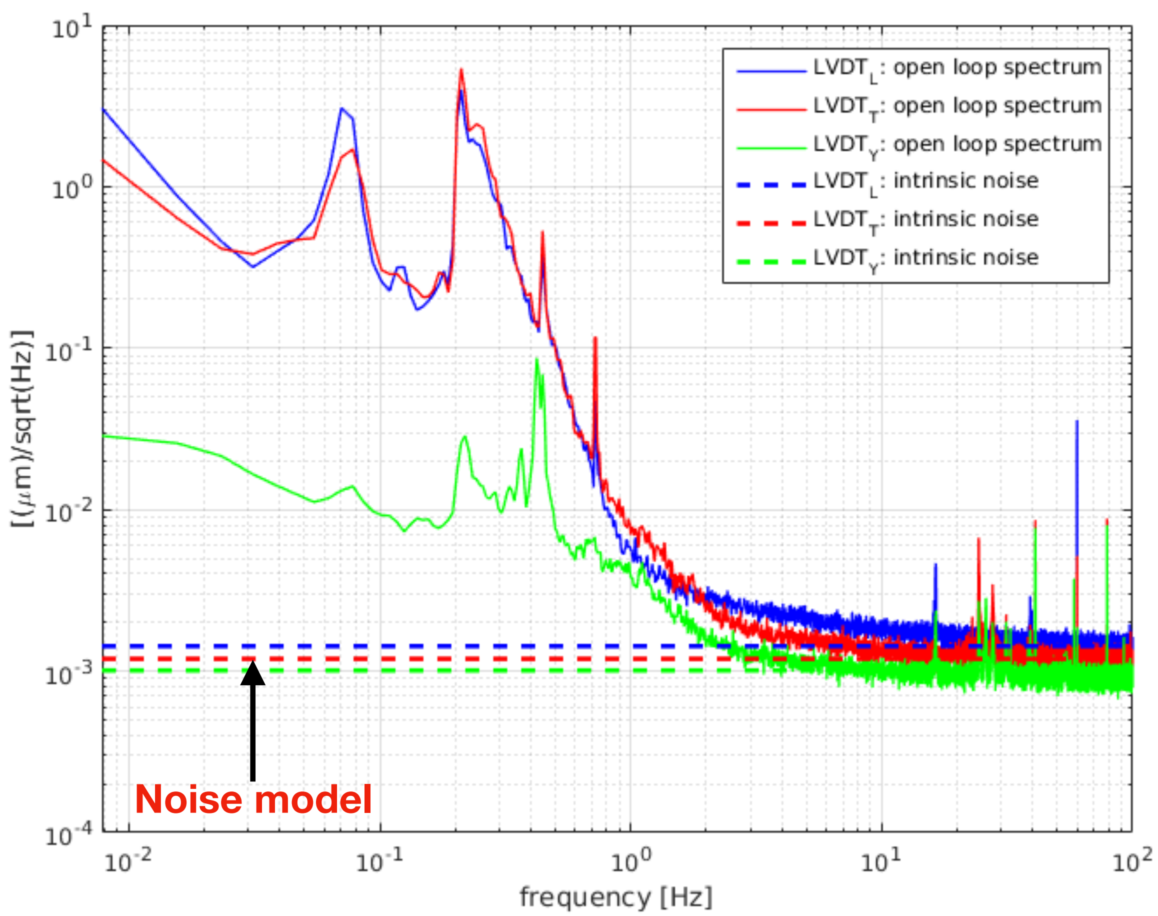
Acc spectrum signal

Versus intrinsic noise (model)

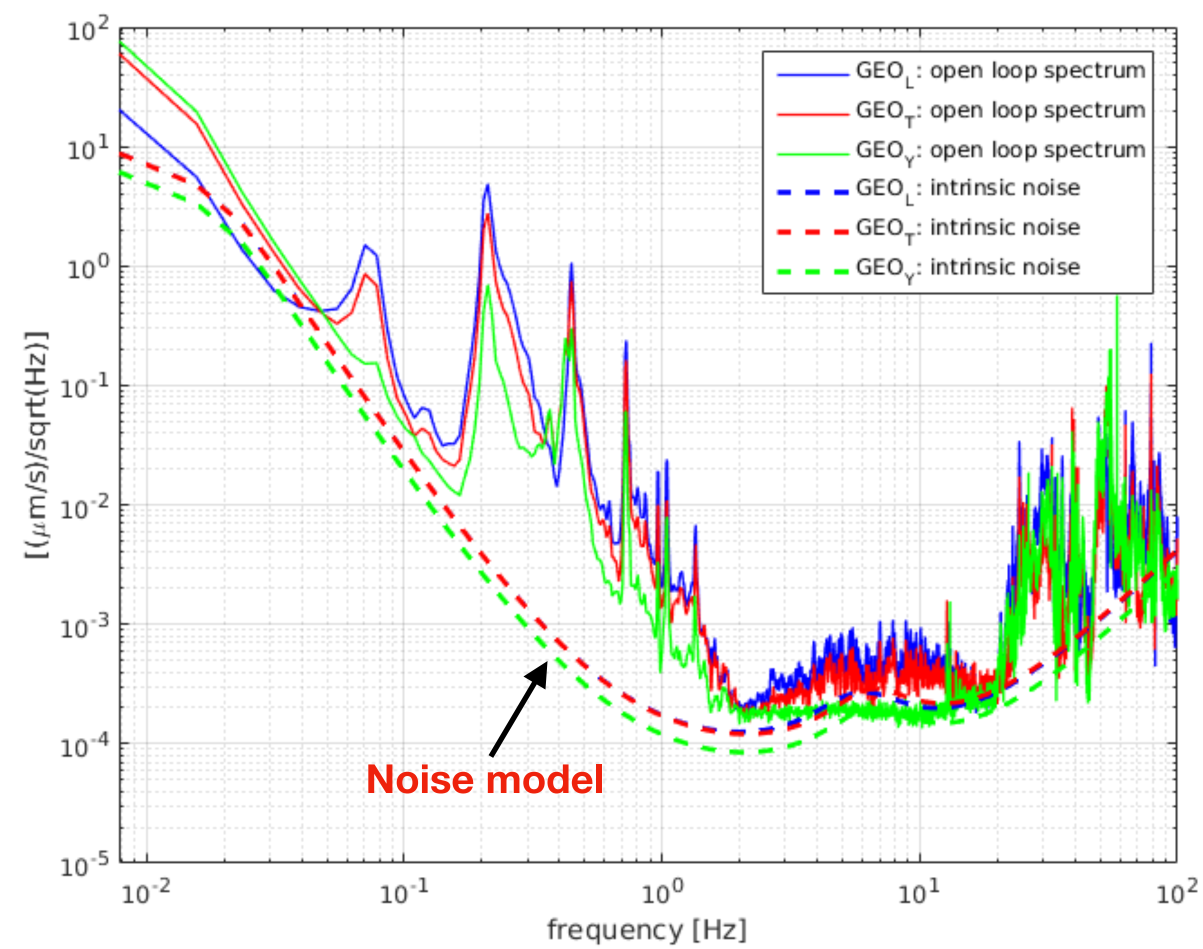
Noise budget of diagonalized sensors (II)

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

ETMX LVDT



ETMX GEO



LVDT spectrum signal

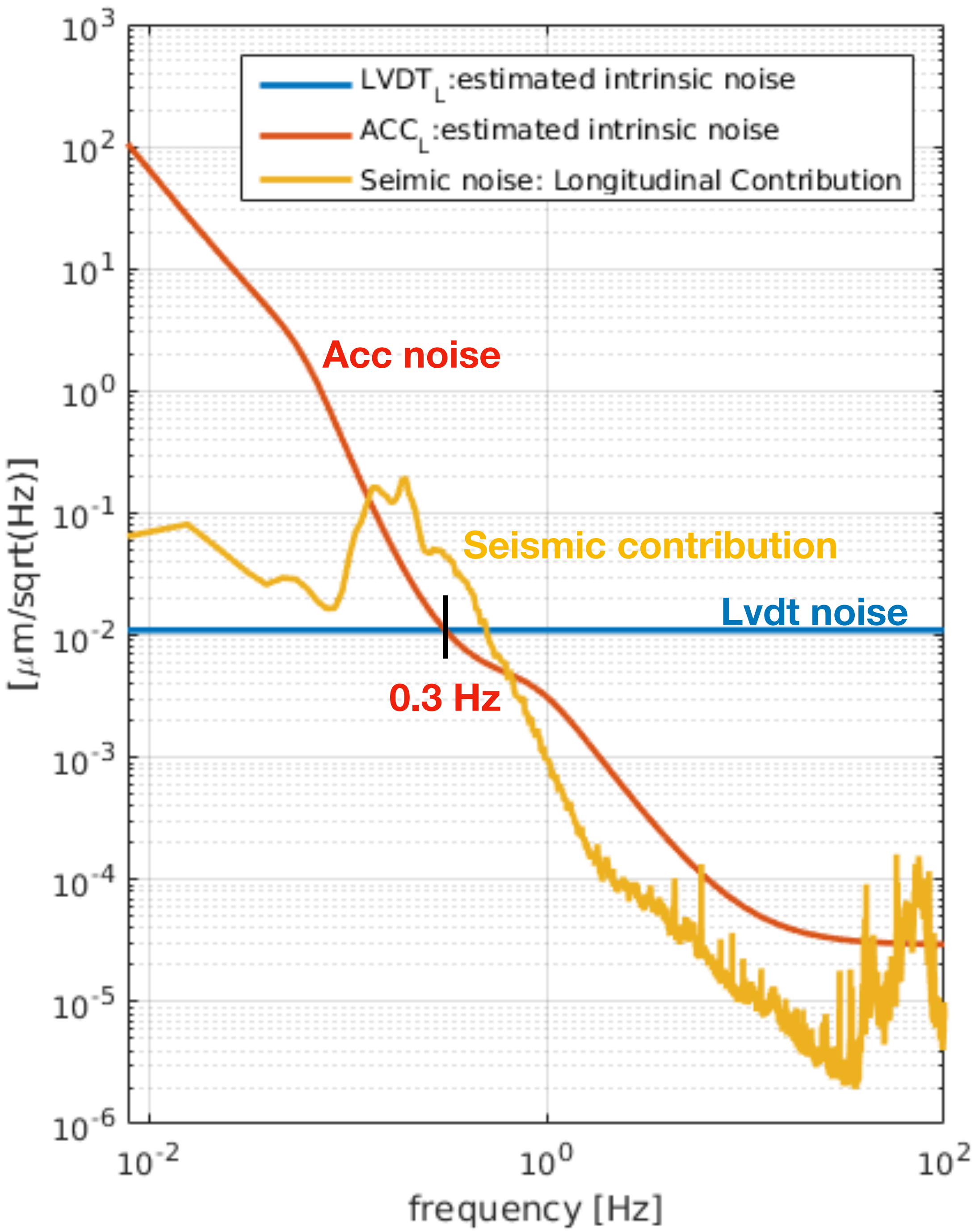
Versus intrinsic noise (model)

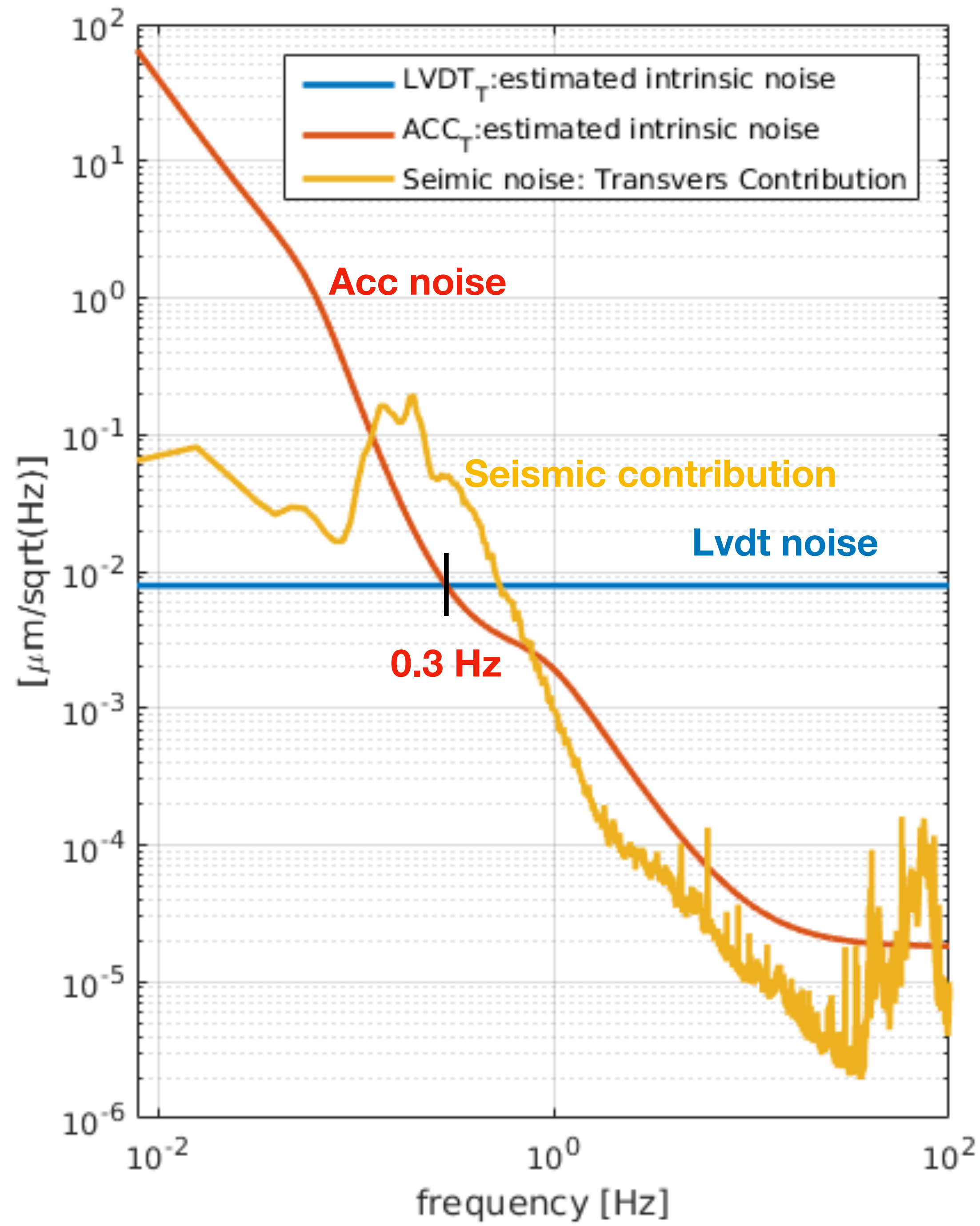
Geo spectrum signal

Versus intrinsic noise (model)

Noise budget of diagonalized sensors (III)

ITMX



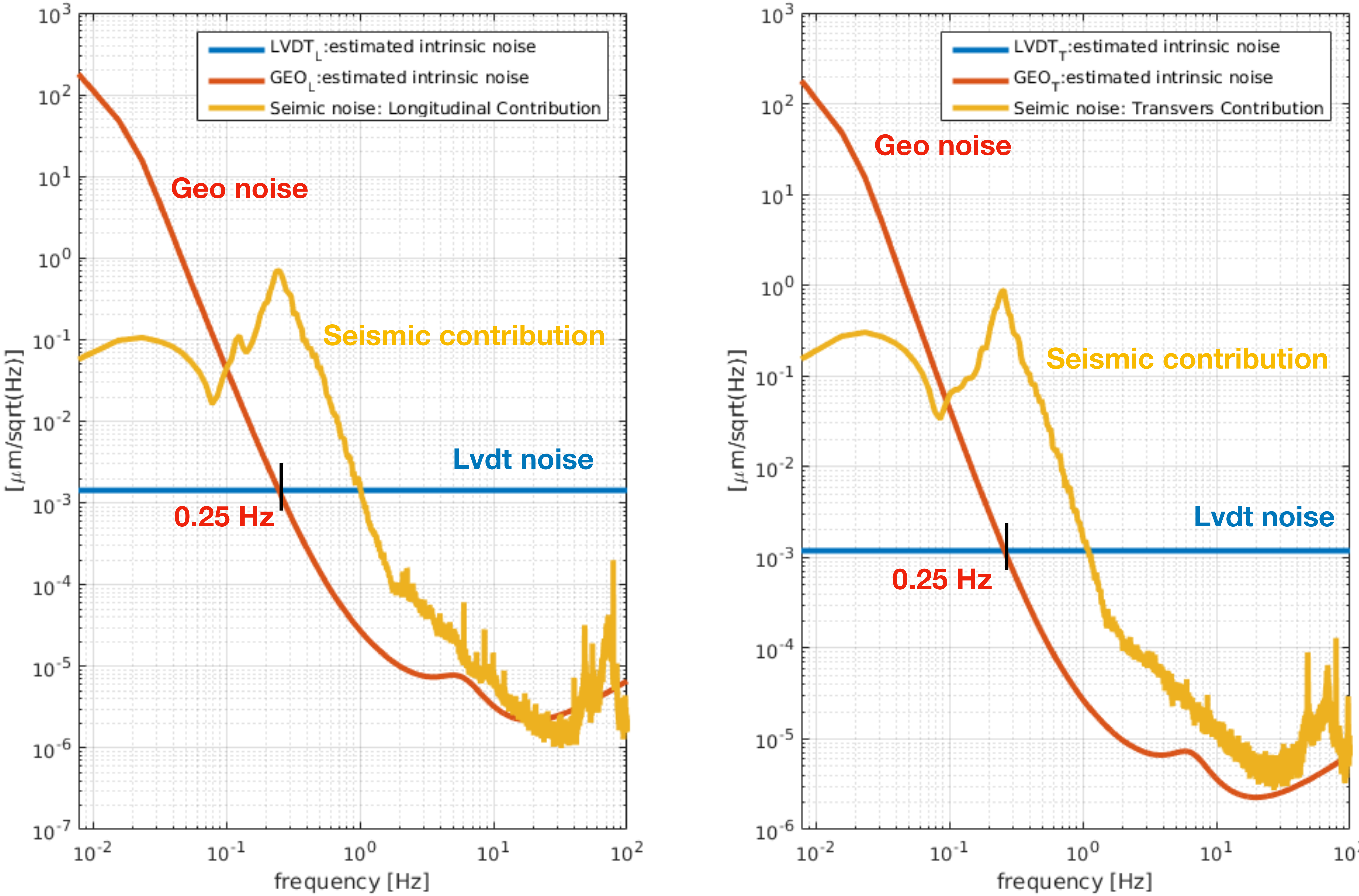


__Below 0.3 mHz, the accelerometernoise is dominant__

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

Noise budget of diagonalized sensors (IV)

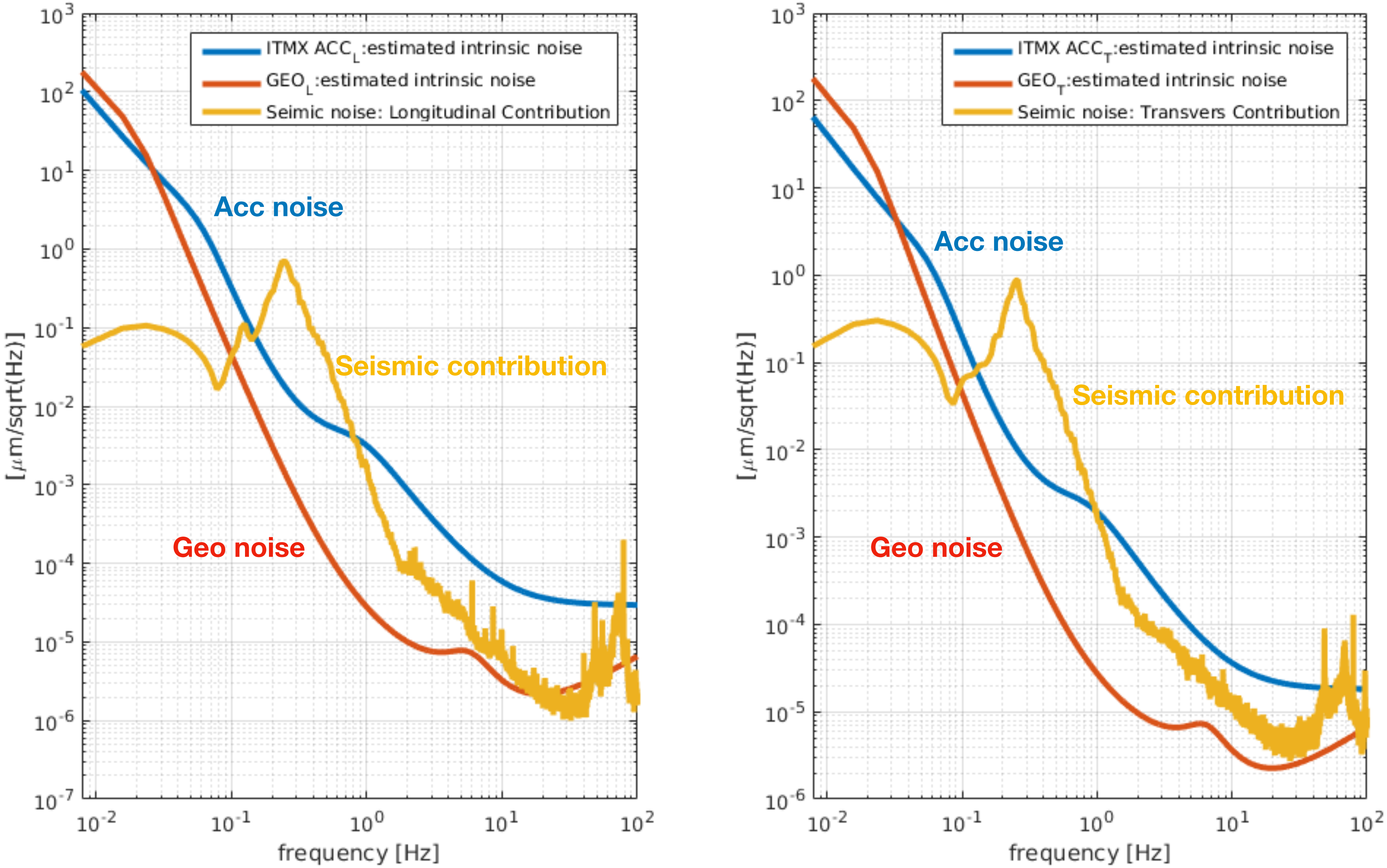
ETMX



Below 0.250 mHz, the geophone noise is dominant

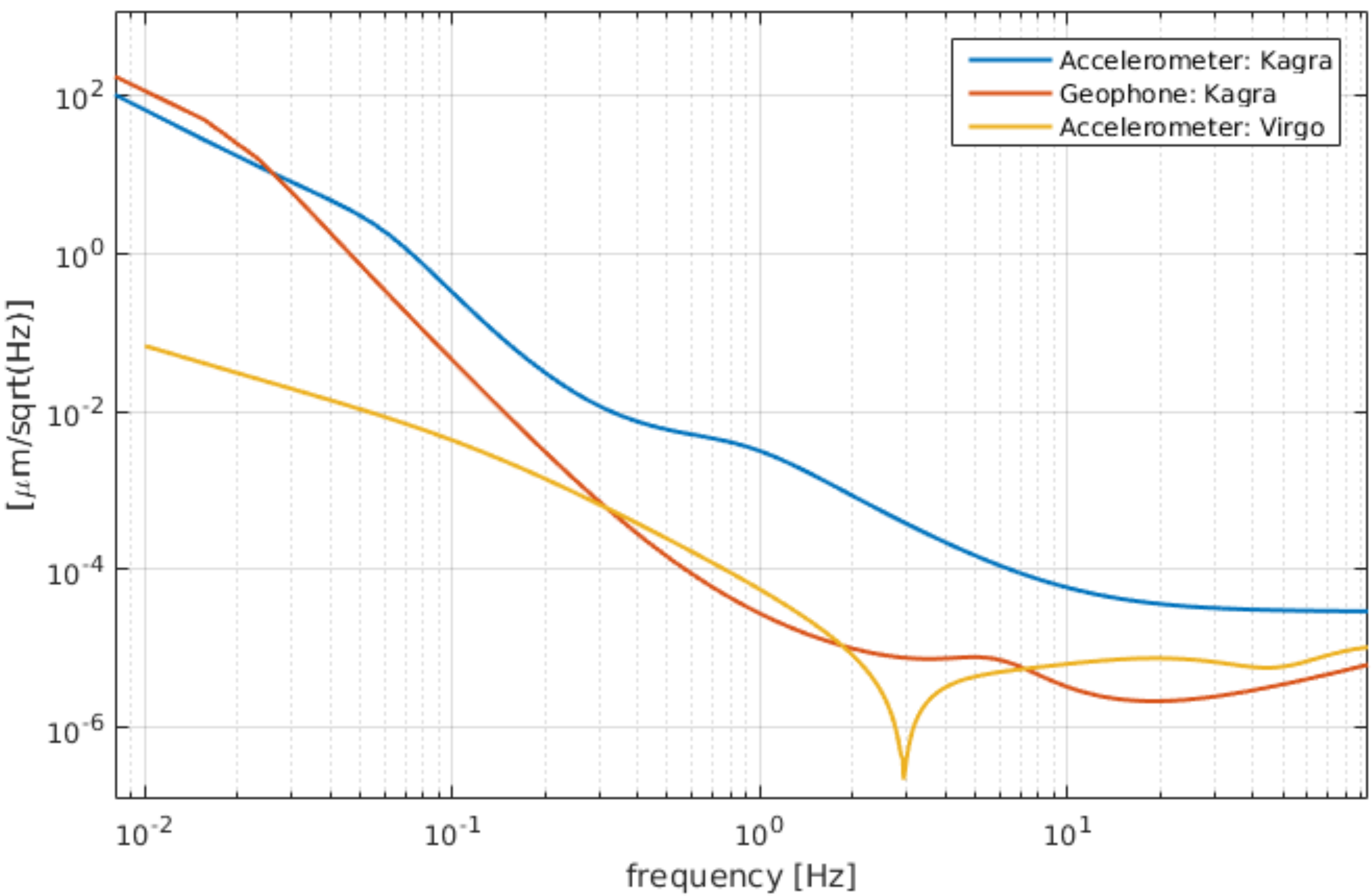
In the range [0.1,0. 5] Hz, the LVDT signal is spoiled by seismic noise.

Noise budget of diagonalized sensors (V)

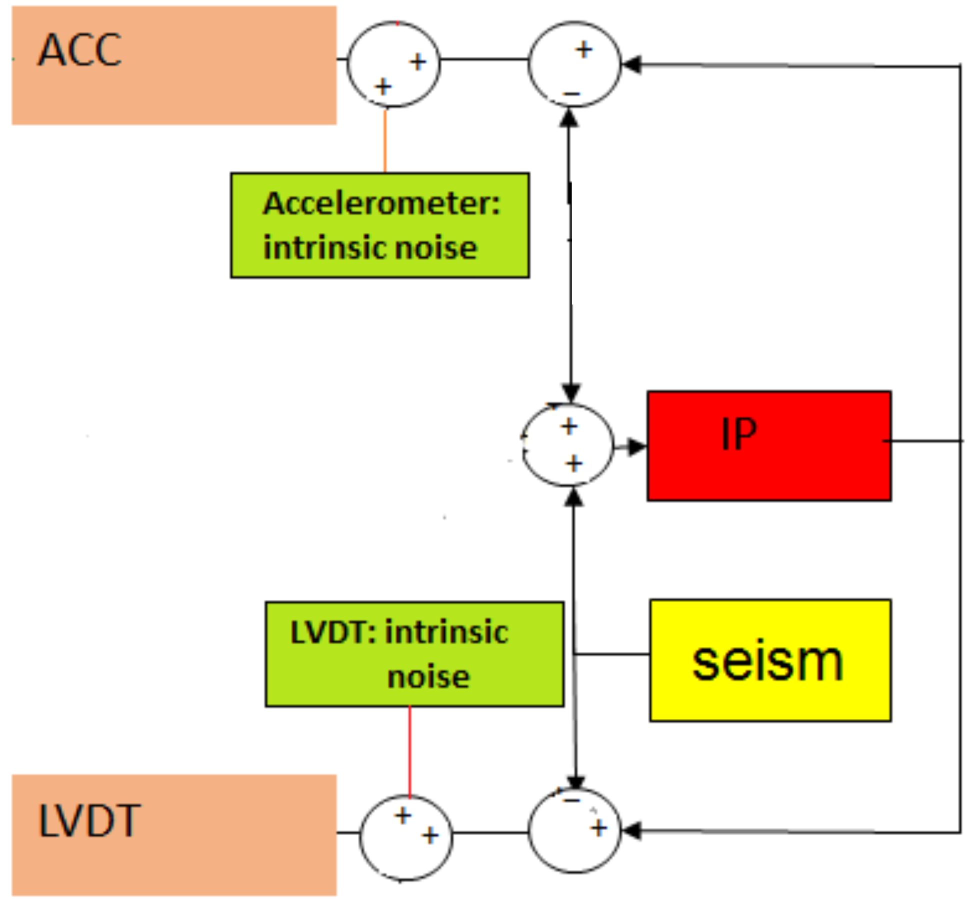


The geophone is less noisy than the accelerometer

Comparison of inertial sensor noise in Virgo and KAGRA



Blending technique



ACC or GEO

High Pass filter (HP)

LVDT

Low Pass filter (LP)

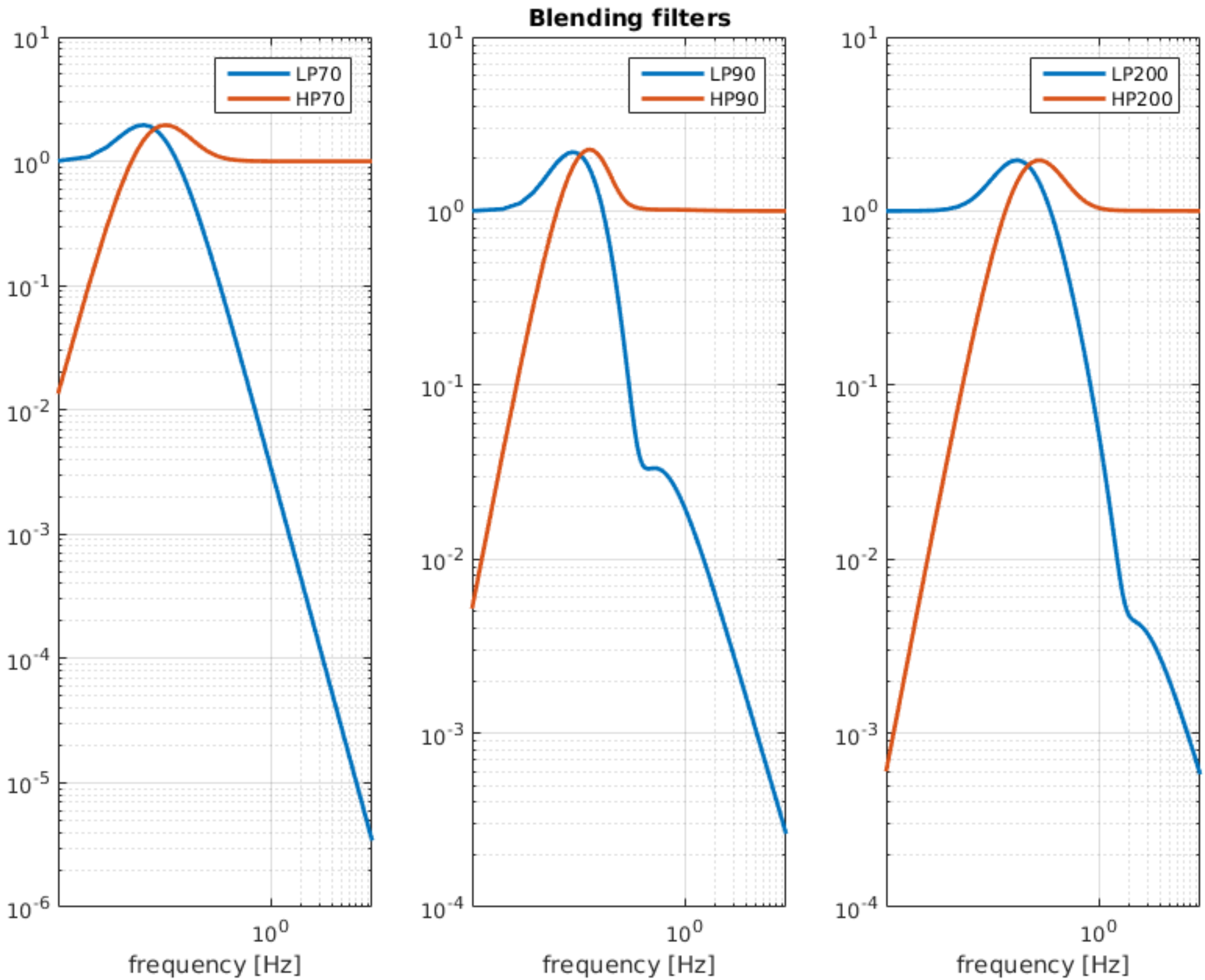
HP+LP=1

- 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.

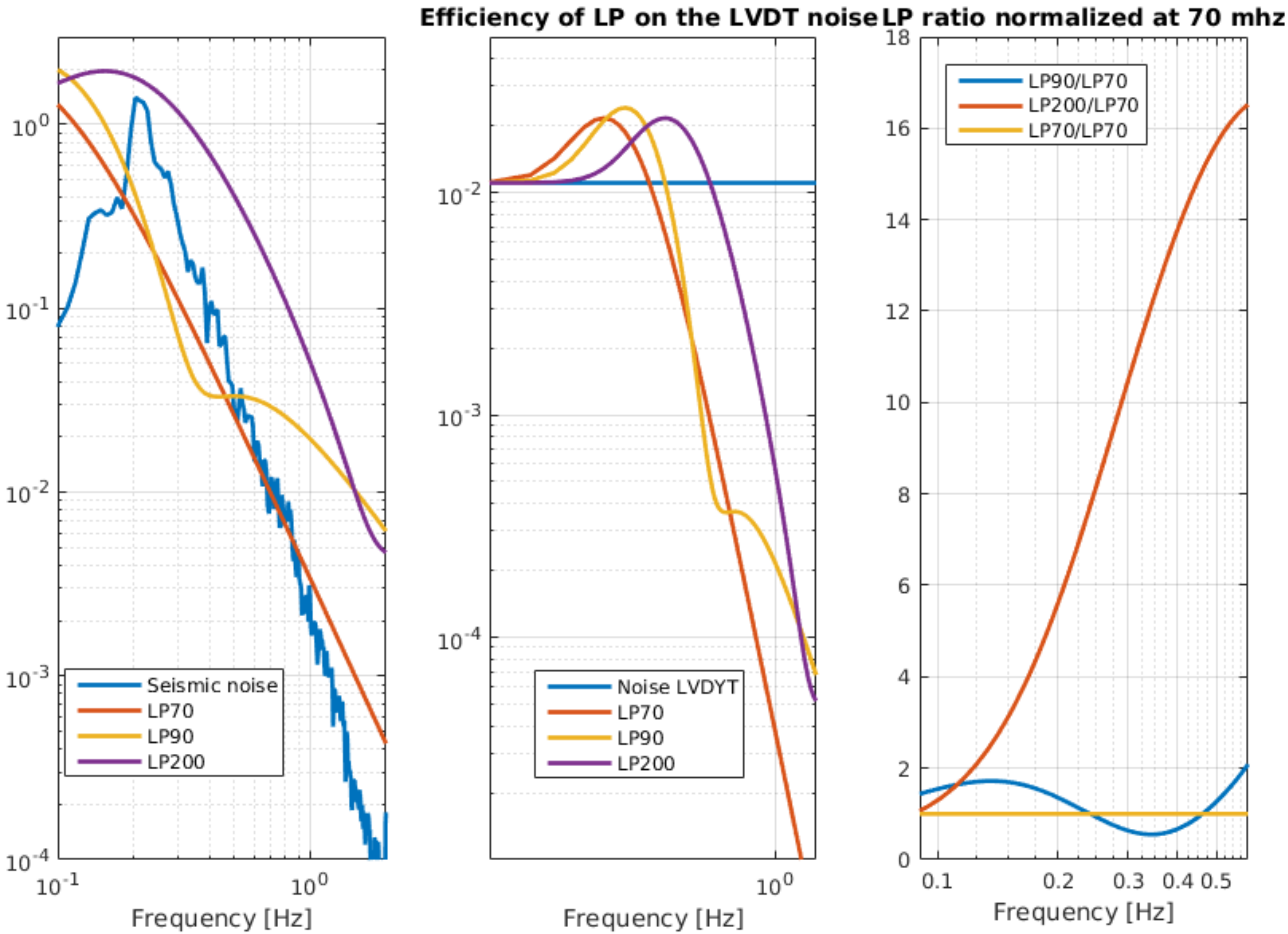
Blended Sensor is defined as :

$$S(\omega) = LP(\omega) \cdot S_{LVDT}(\omega) - \omega^{-2} HP(\omega) \cdot S_{Acc}(\omega)$$

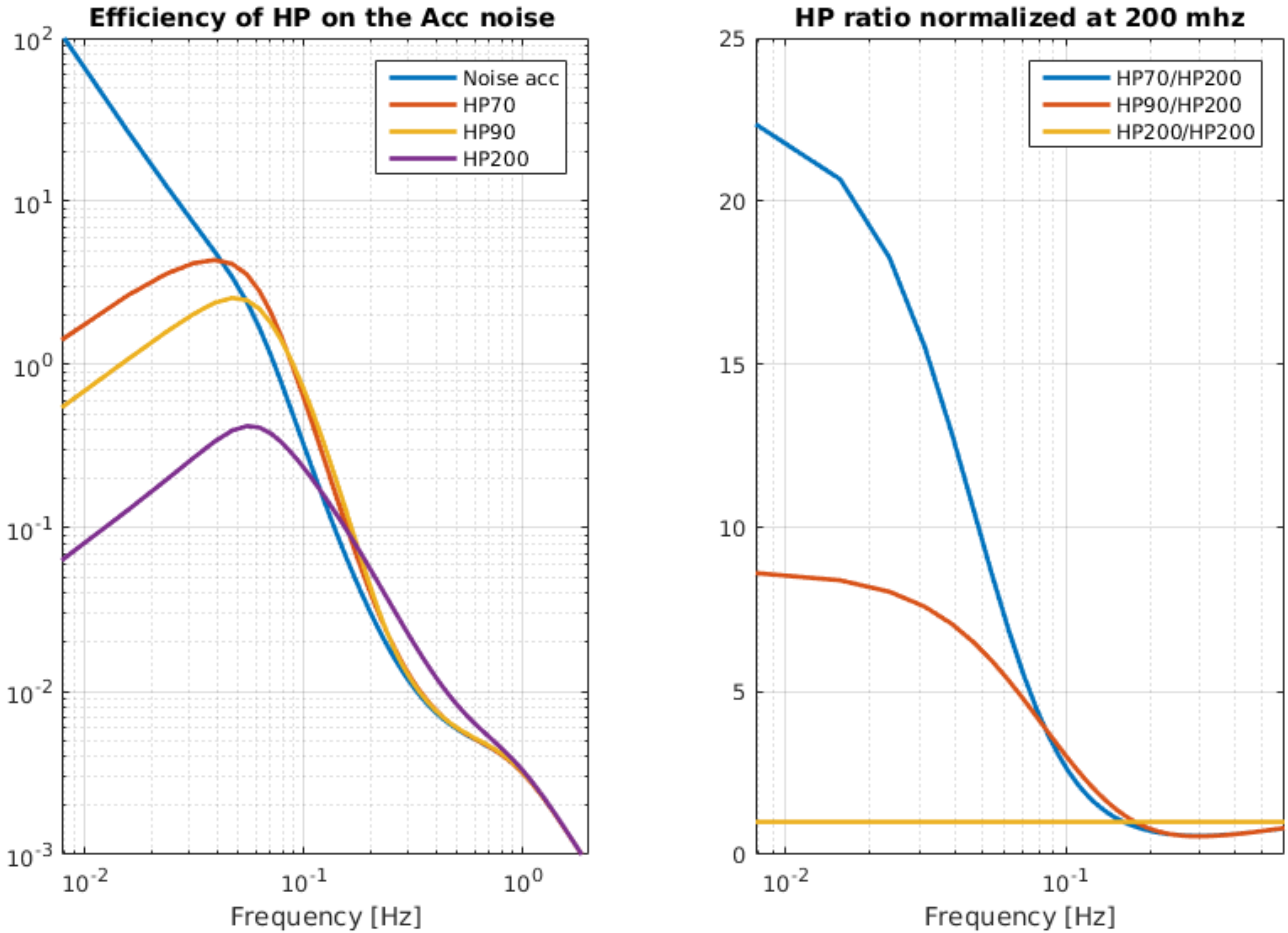
Blending Filters (I)



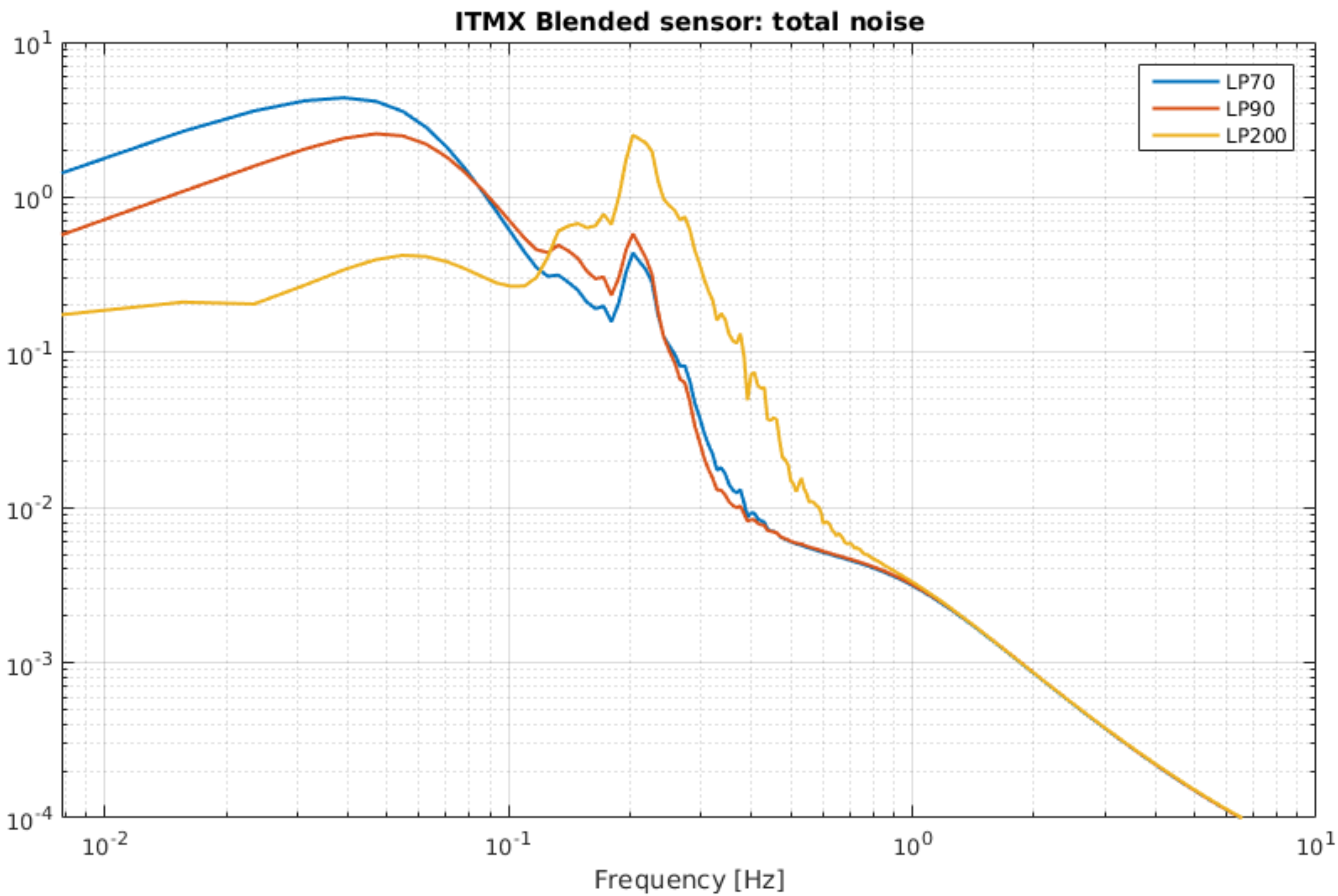
Blending technique: ITMX (I)



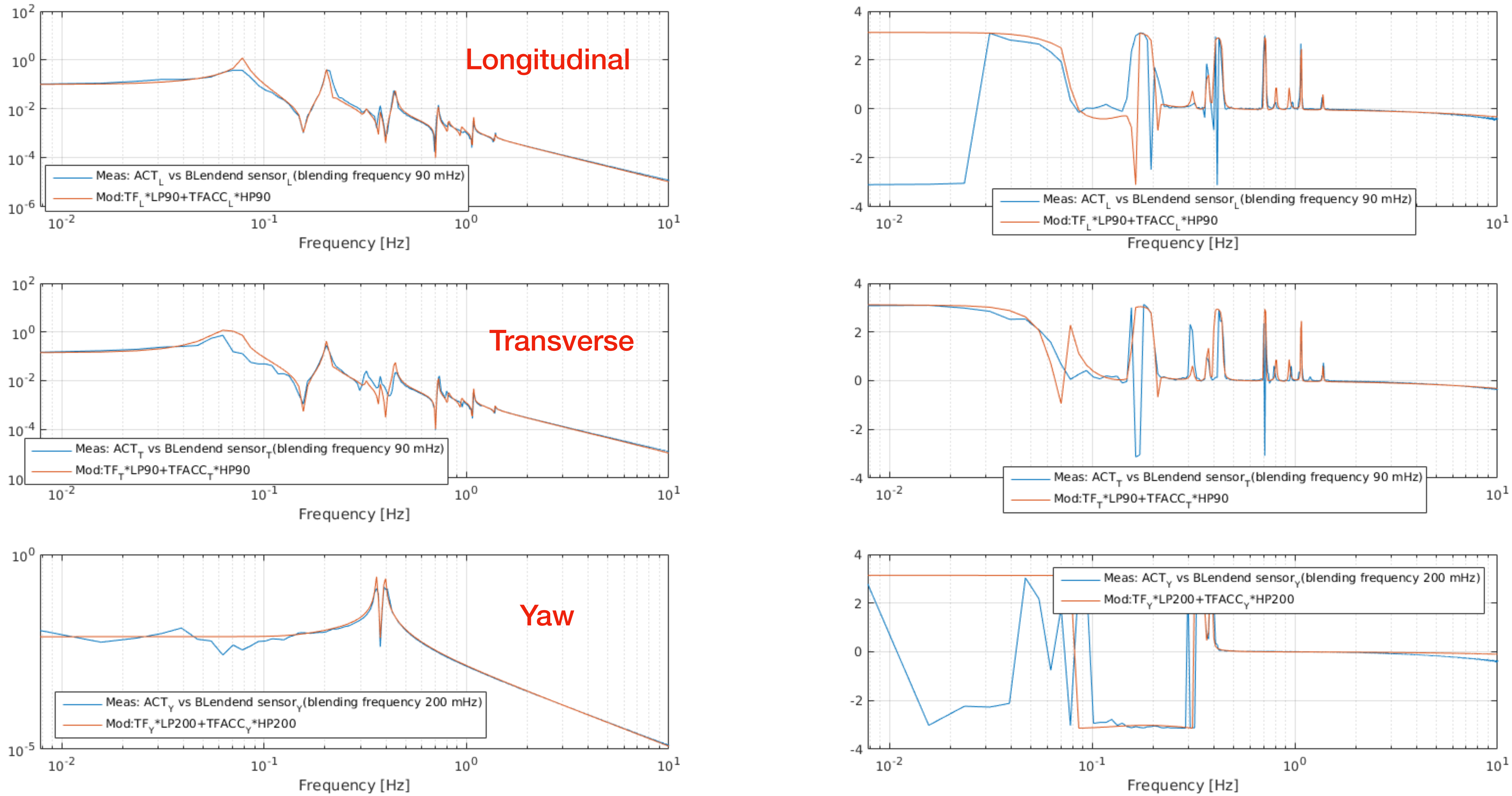
Blending technique: ITMX (II)



ITMX Blended sensors noise limit

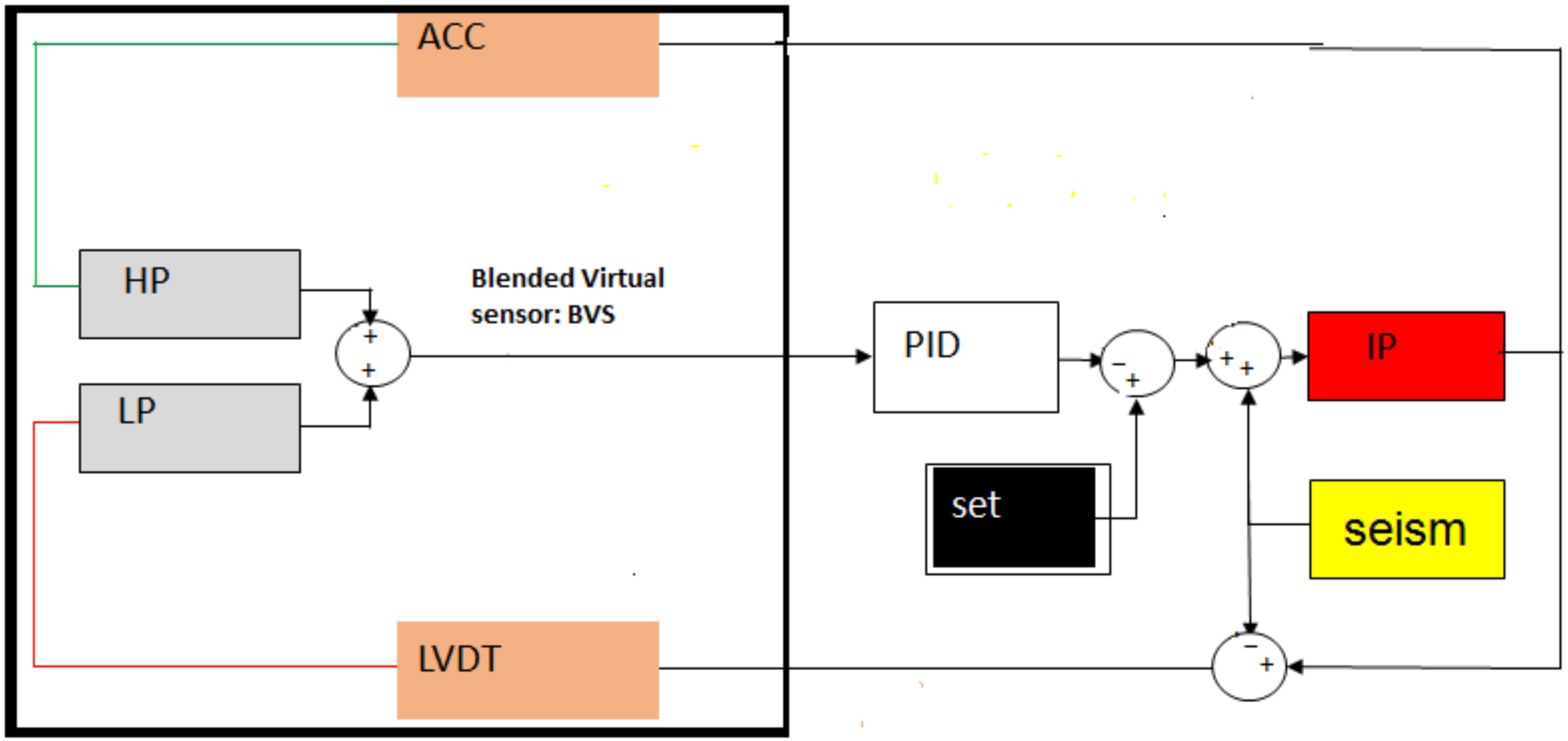


ITMX: IP blended TFs



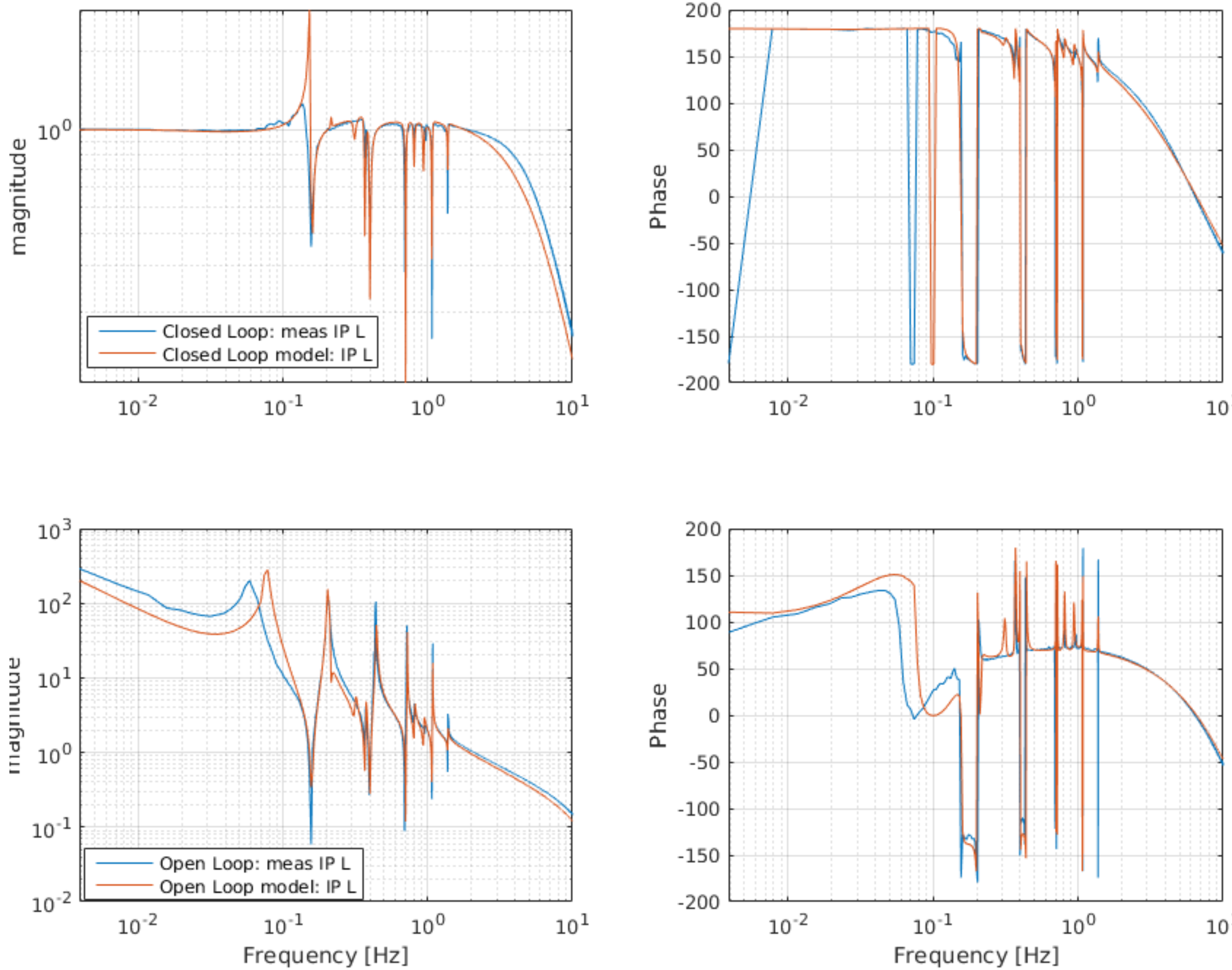
Blending filter frequency: 90 mHz for L and T and 200 mHz for Y

Closed loop blended Signal



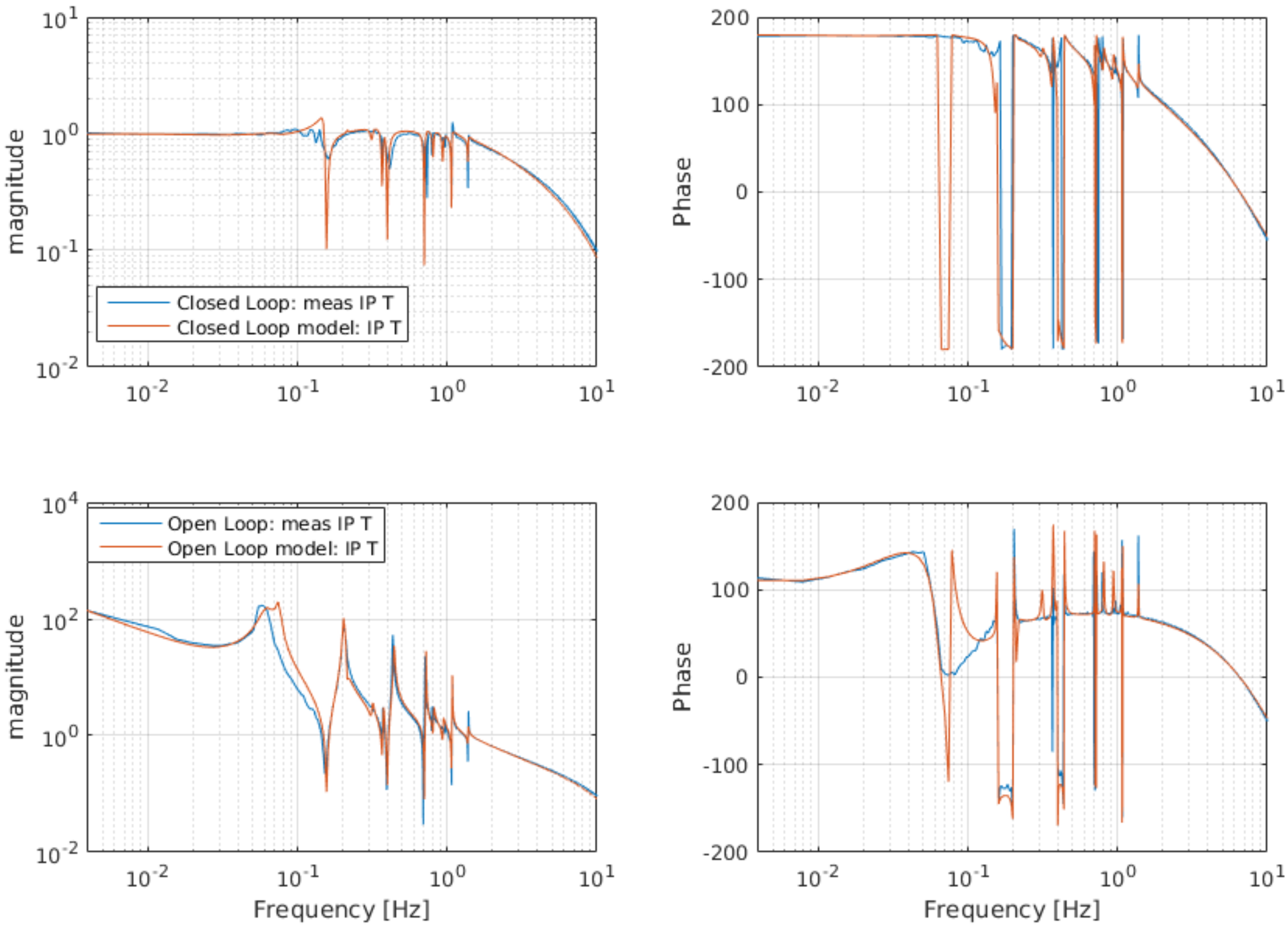
$$\tilde{S}_{iv}^{CL}(\omega) = \frac{\tilde{S}_{iv}(\omega)}{1 - \tilde{M}_i(\omega) \cdot \tilde{C}_i(\omega)}$$

ITMX IP Longitudinal: Open loop and Closed Loop Transfer functions



Blending frequency 90 mHz **UGF 1 Hz**

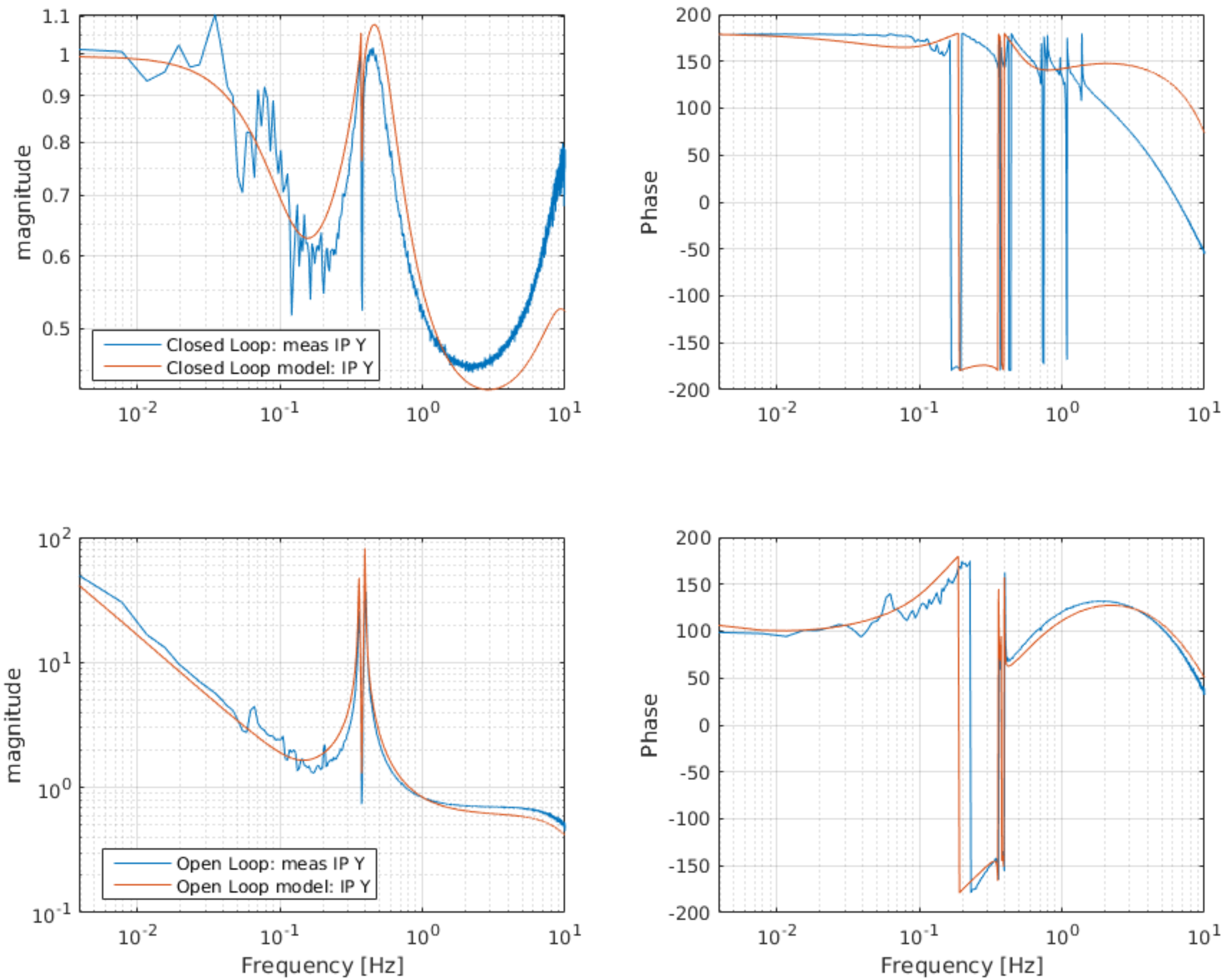
ITMX IP Transverse: Open loop and Closed Loop Transfer functions



Blending frequency 90 mHz

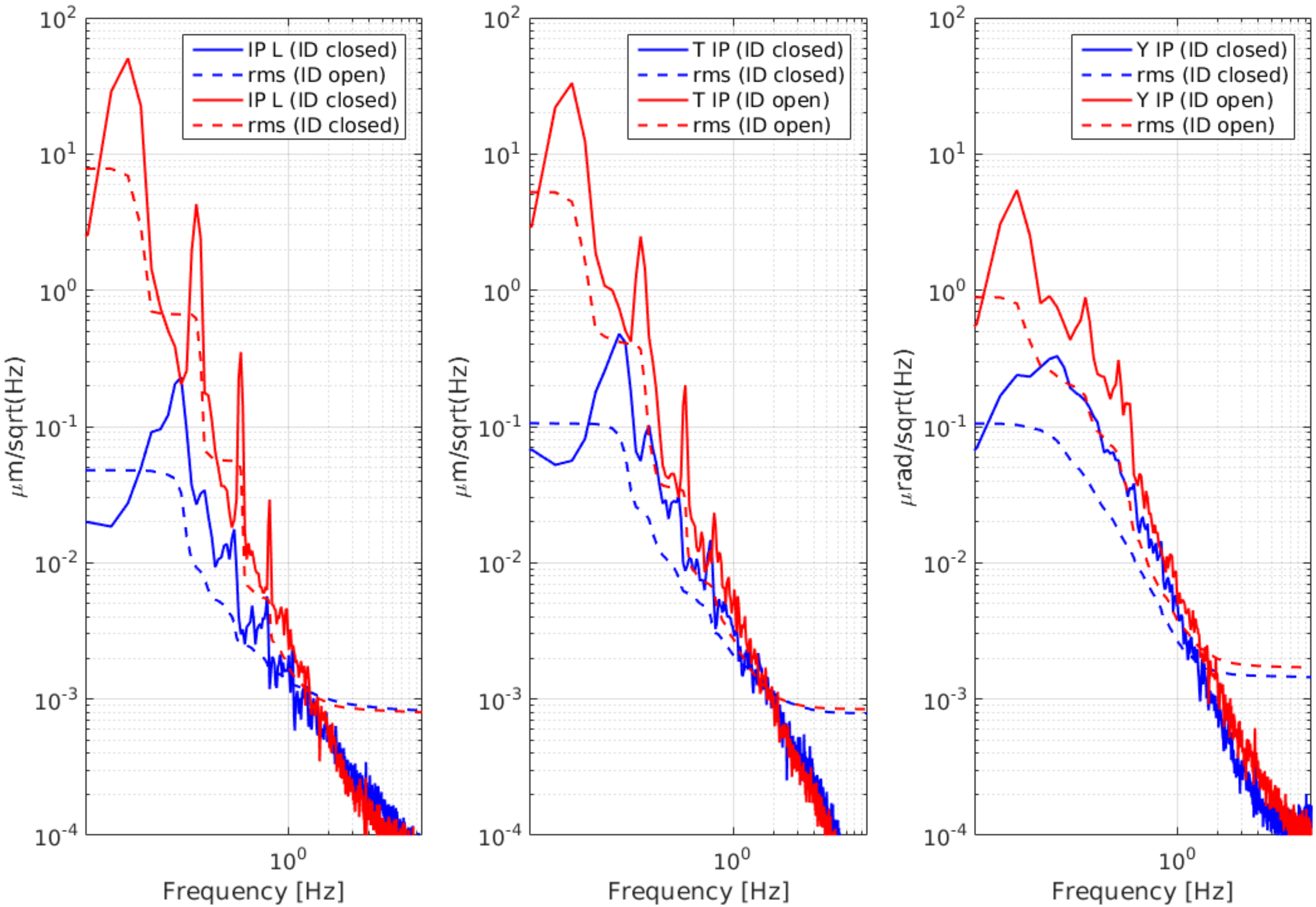
UGF 1 Hz

ITMX IP Yaw: Open loop and Closed Loop Transfer functions

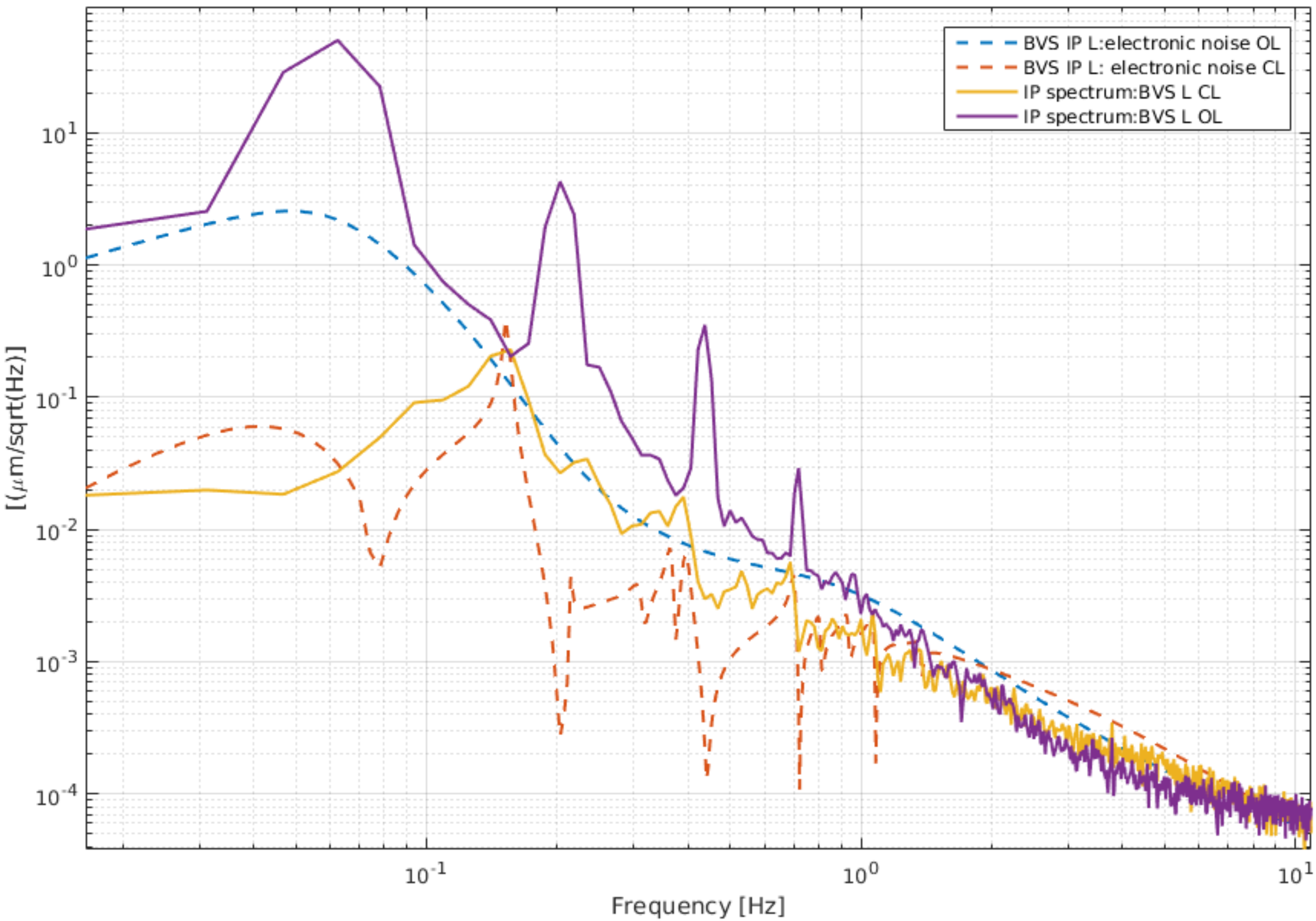


Blending frequency 200 mHz **UGF 0.8 Hz**

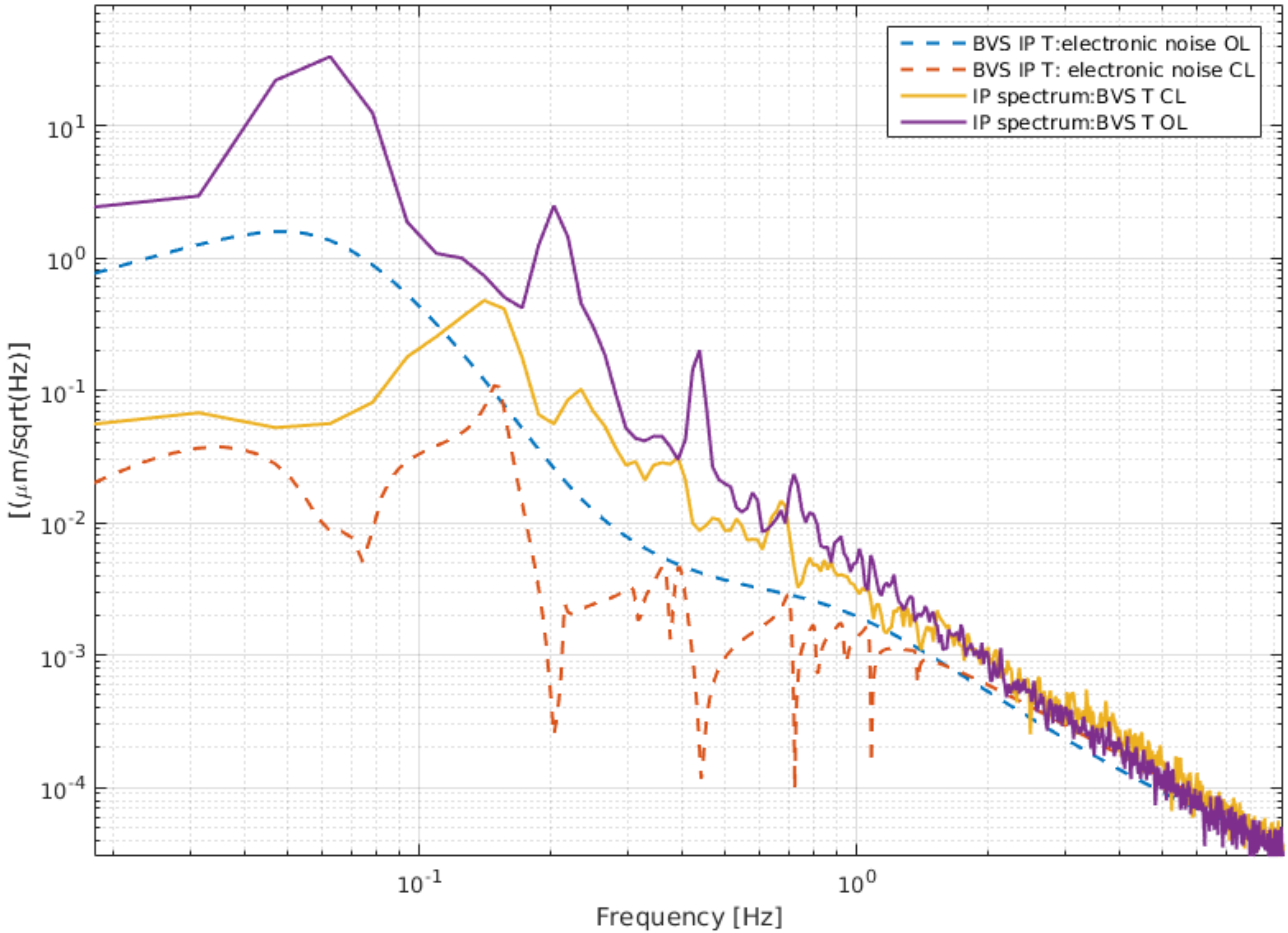
Open loop and Closed Loop ITMX IP Spectra



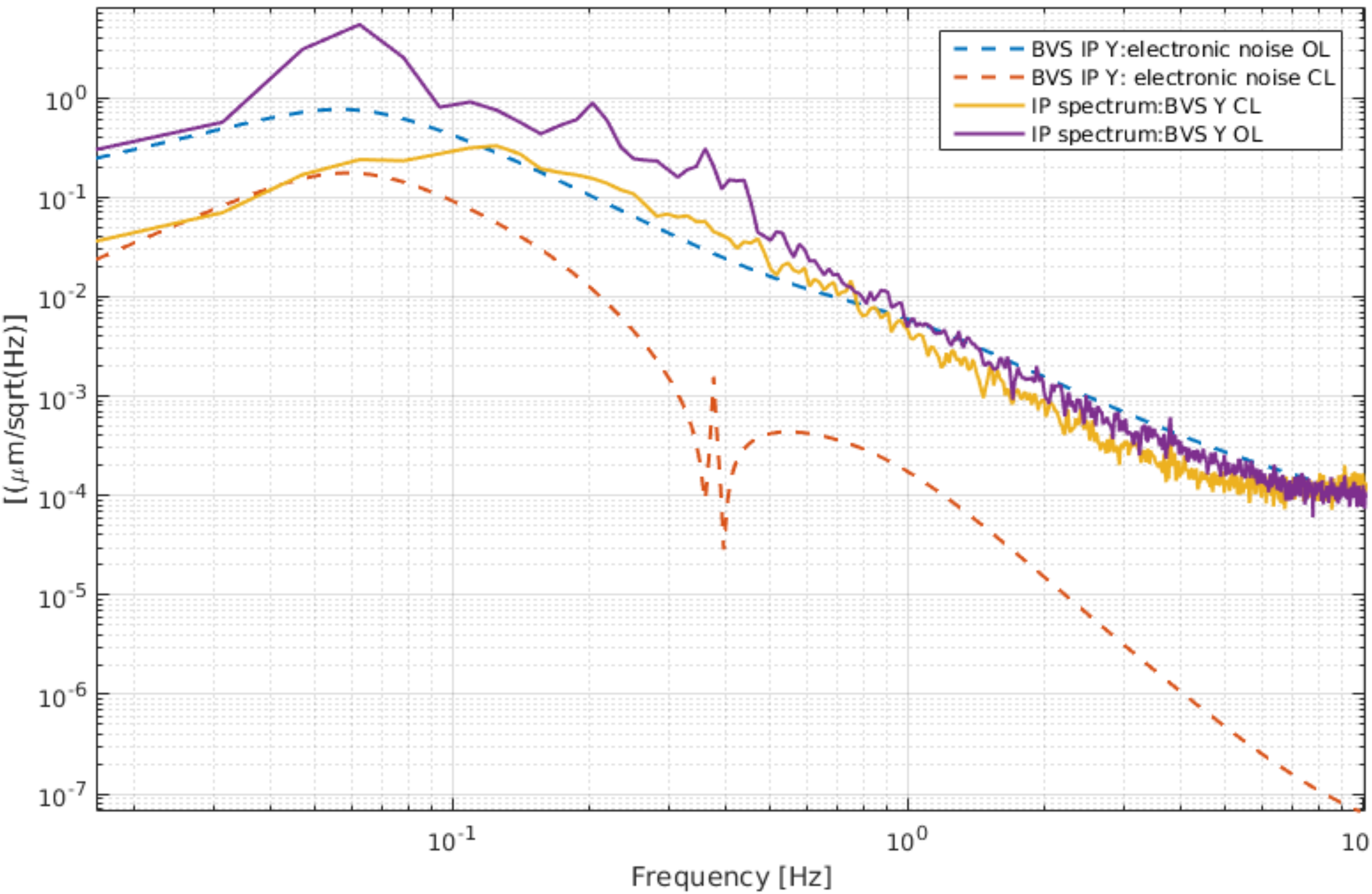
Open loop and Closed Loop ITMX IP Spectra Longitudinal: noise budget



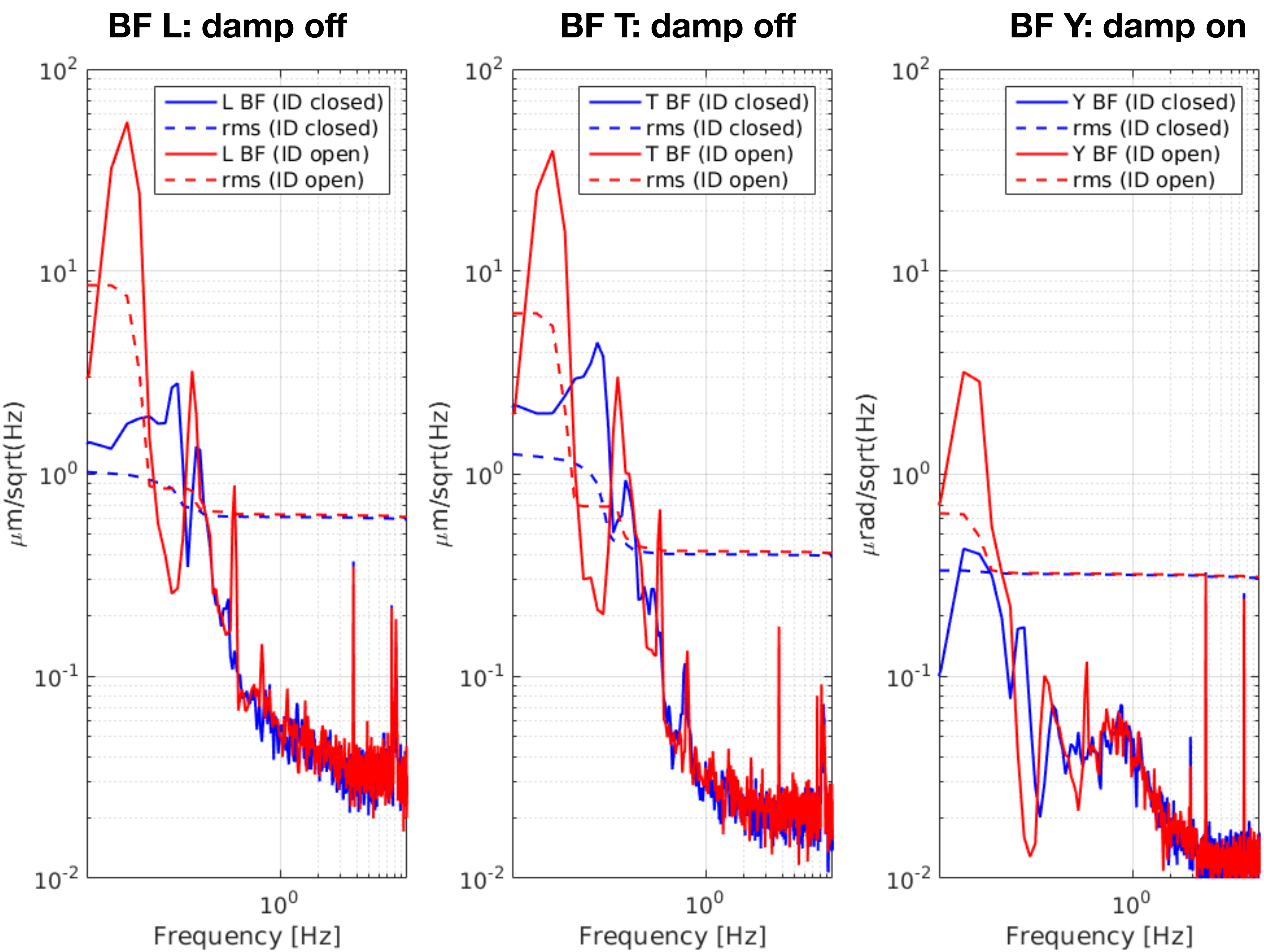
Open loop and Closed Loop ITMX IP Spectra Transverse: noise budget



Open loop and Closed Loop ITMX IP Spectra Yaw: noise budget

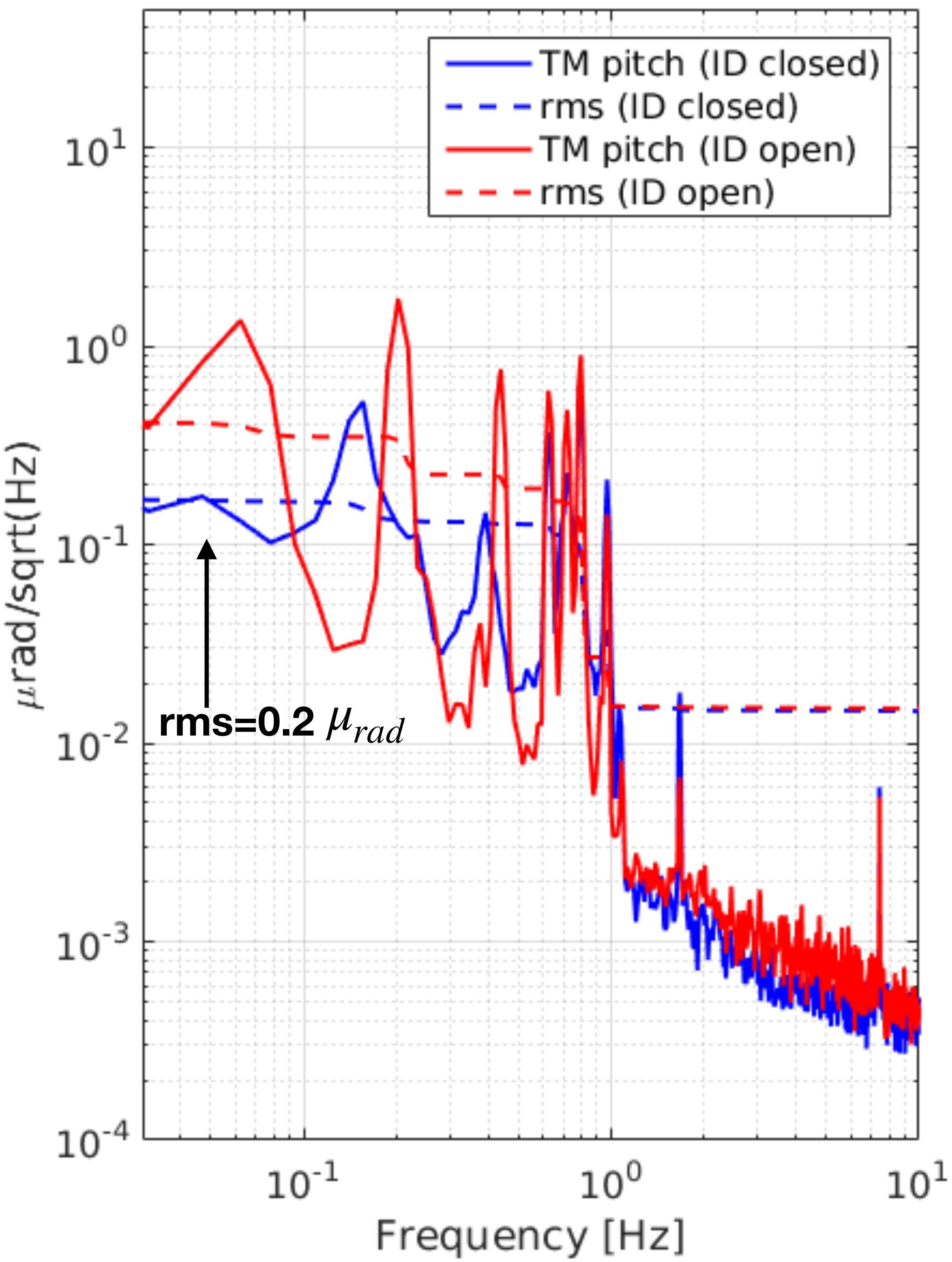


Open loop and Closed Loop ITMX BF Spectra: Longitudinal

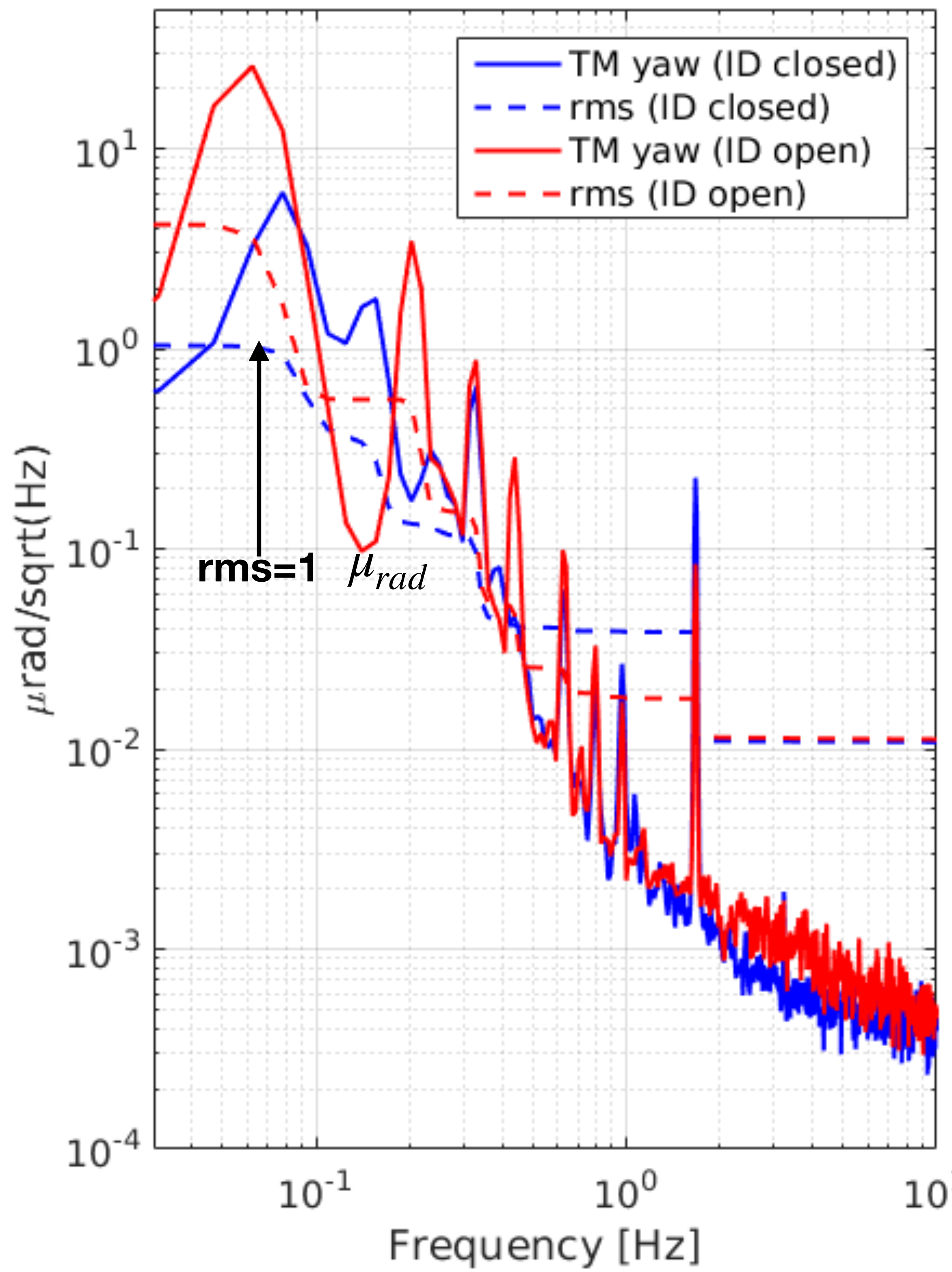


Open loop and Closed Loop ITMX TM Spectra: P and Yaw

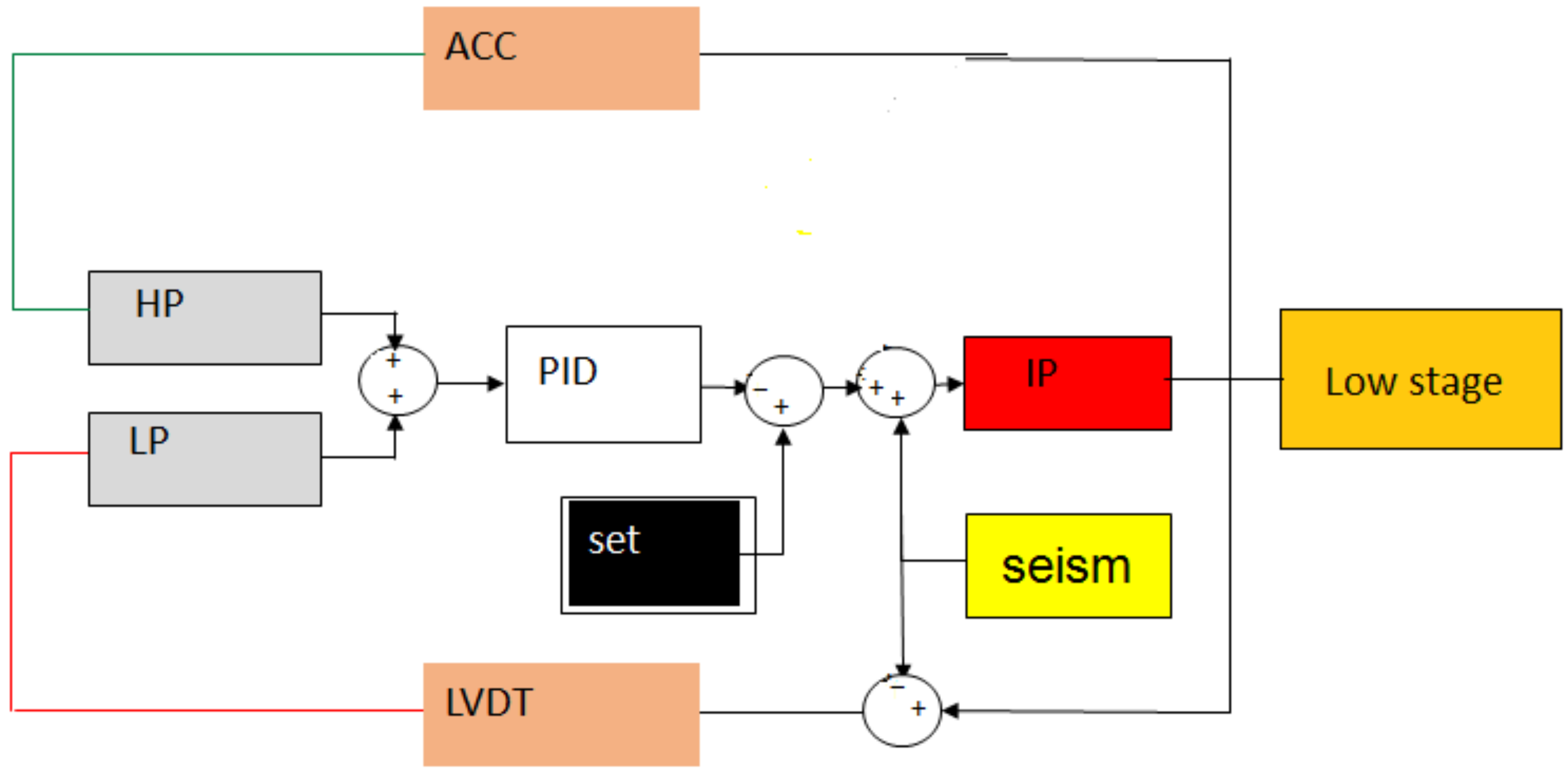
MN &TM P: damp off



MN &TM Y: damp off



Inertial damping: residual motion of the bottom stage (I)



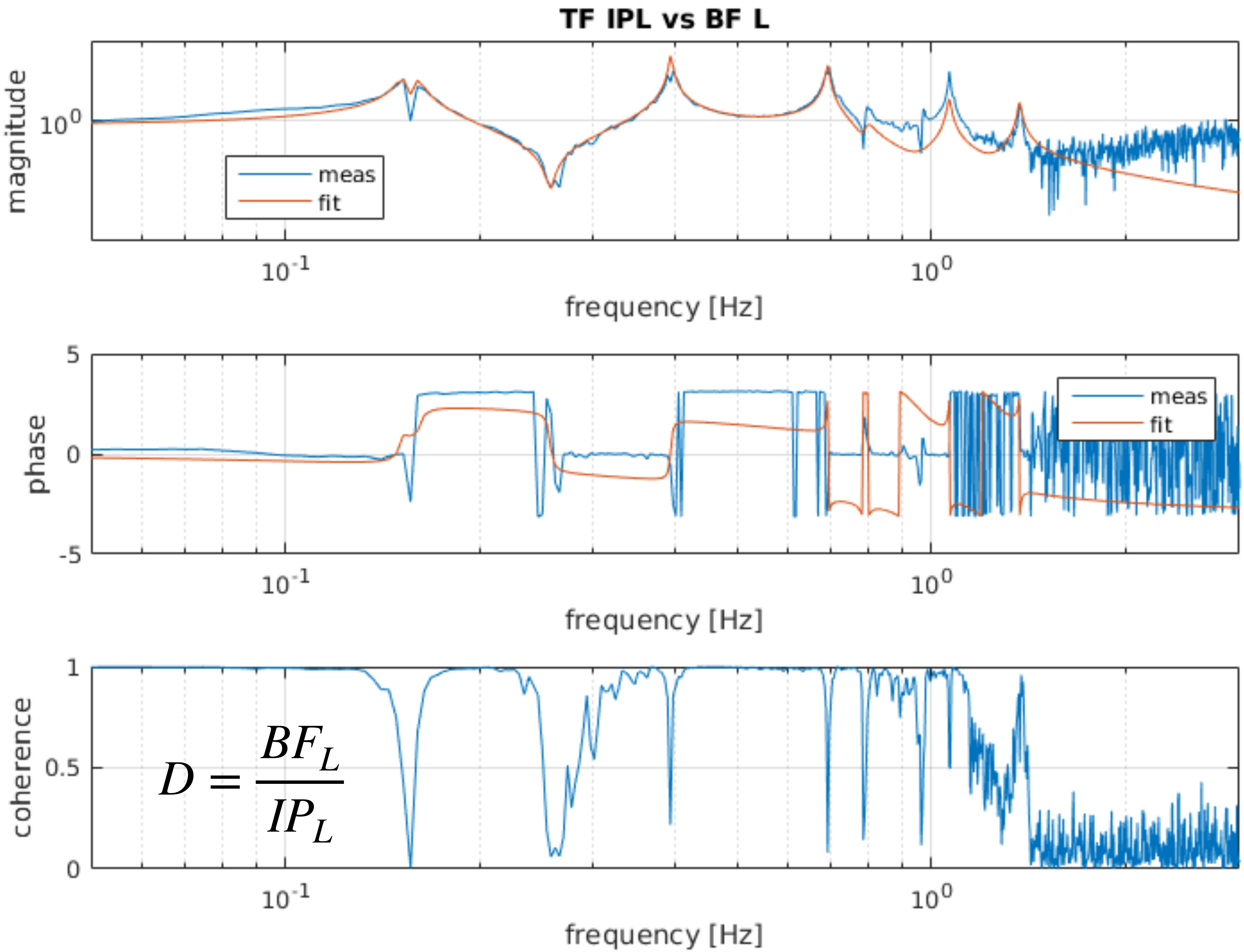
The residual motion of the low stage is:

$$\tilde{s}_{i,\,\text{lowstage}}(\omega) = \tilde{D}(\omega) \cdot \tilde{s}_i(\omega)$$

Where s_i is the signal provided from the horizontal diagonalized accelerometers.

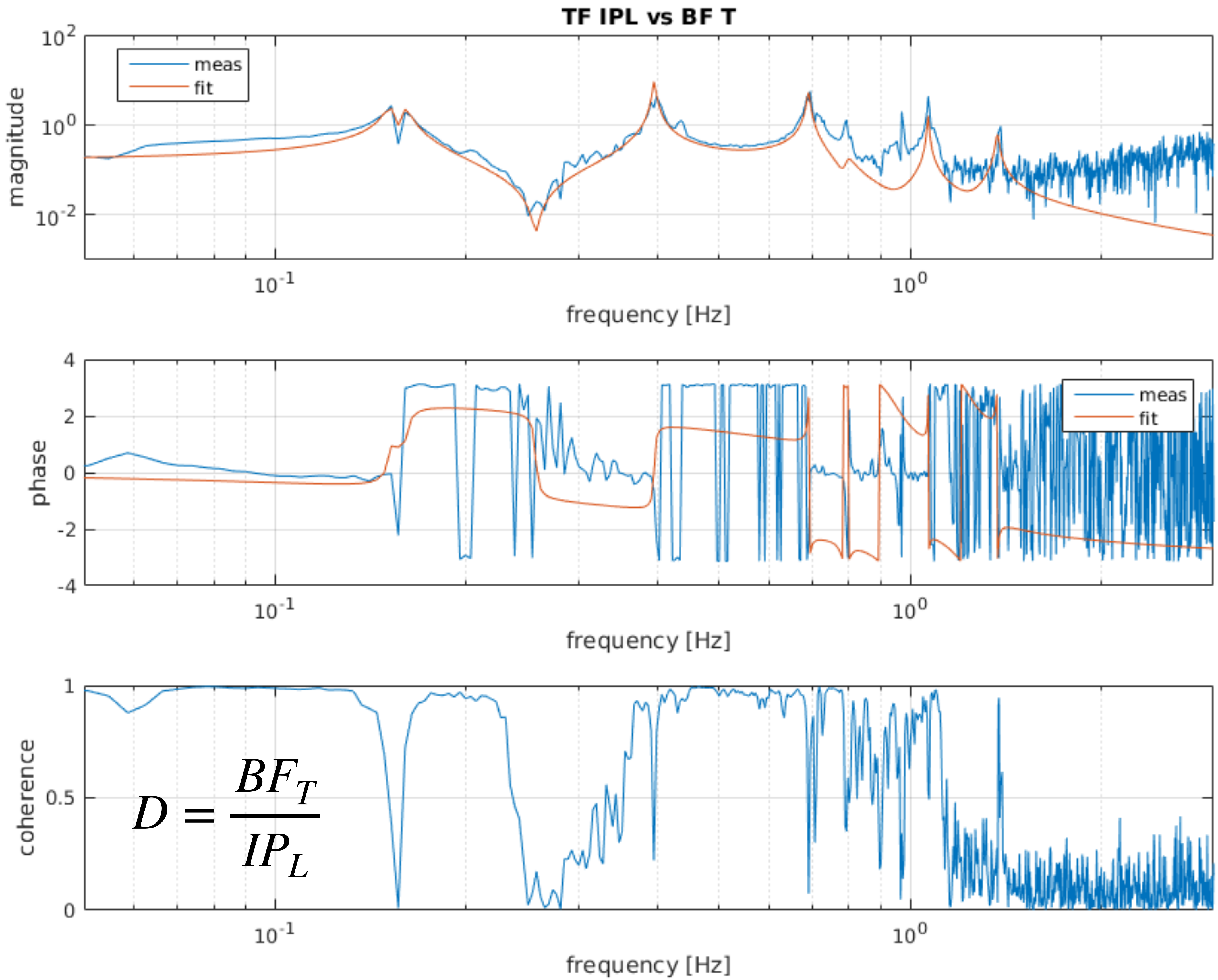
Where D transfer function from top stage (input) to low stage (output)

Inertial damping: residual motion of the bottom stage (II)



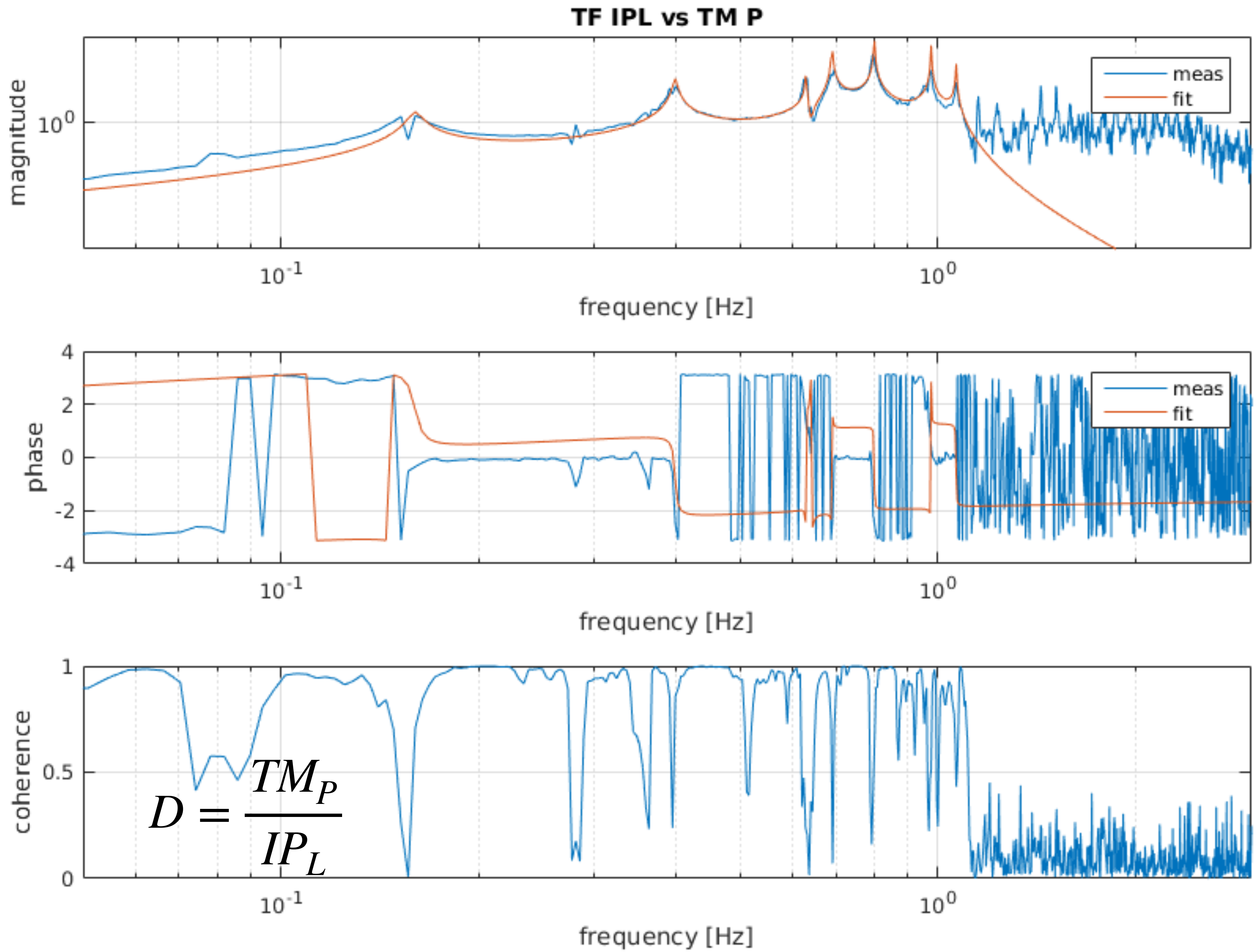
$$D = \frac{BF_L}{IP_L}$$

Inertial damping: residual motion of the bottom stage (III)



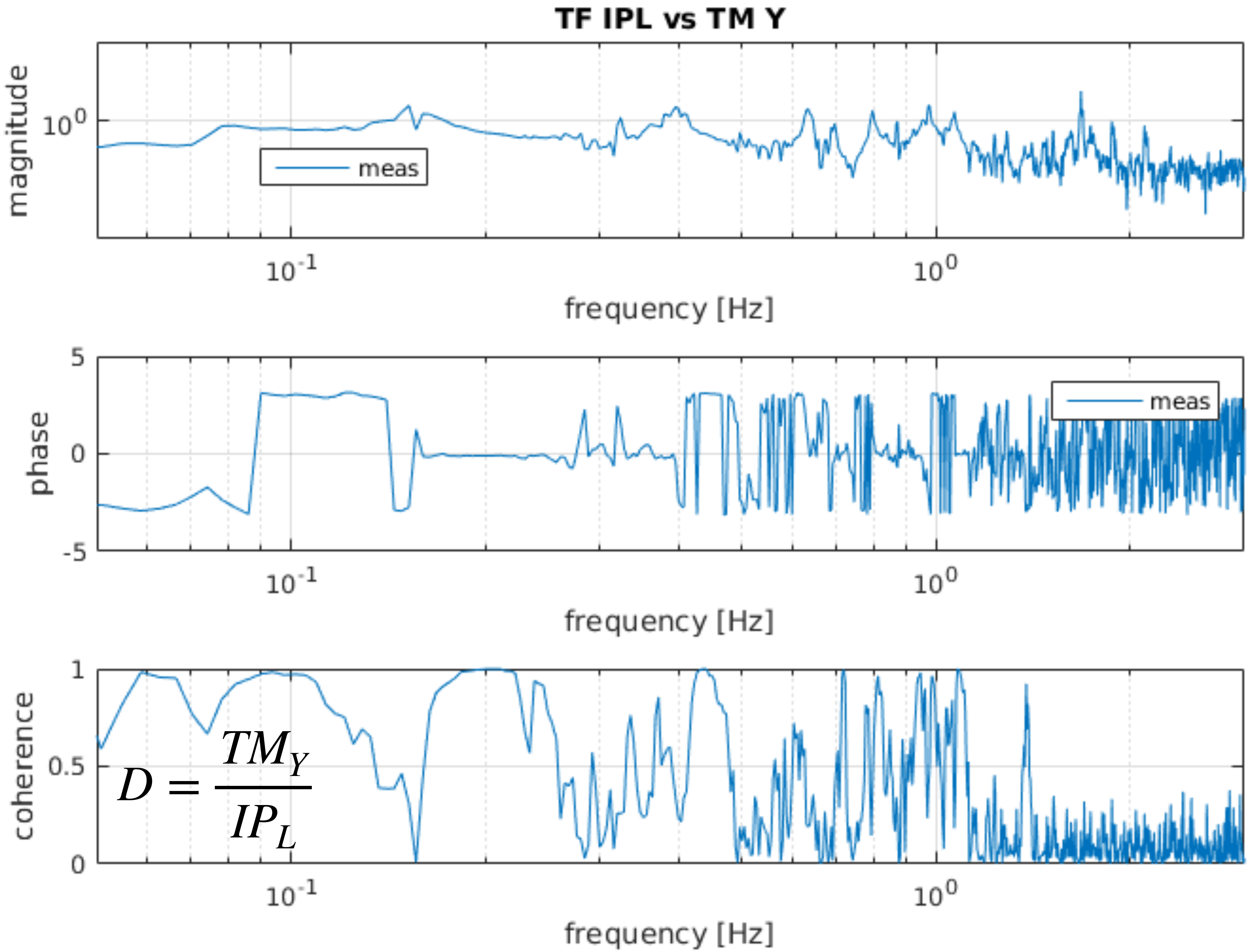
$$D = \frac{BF_T}{IP_L}$$

Inertial damping: residual motion of the bottom stage (IV)



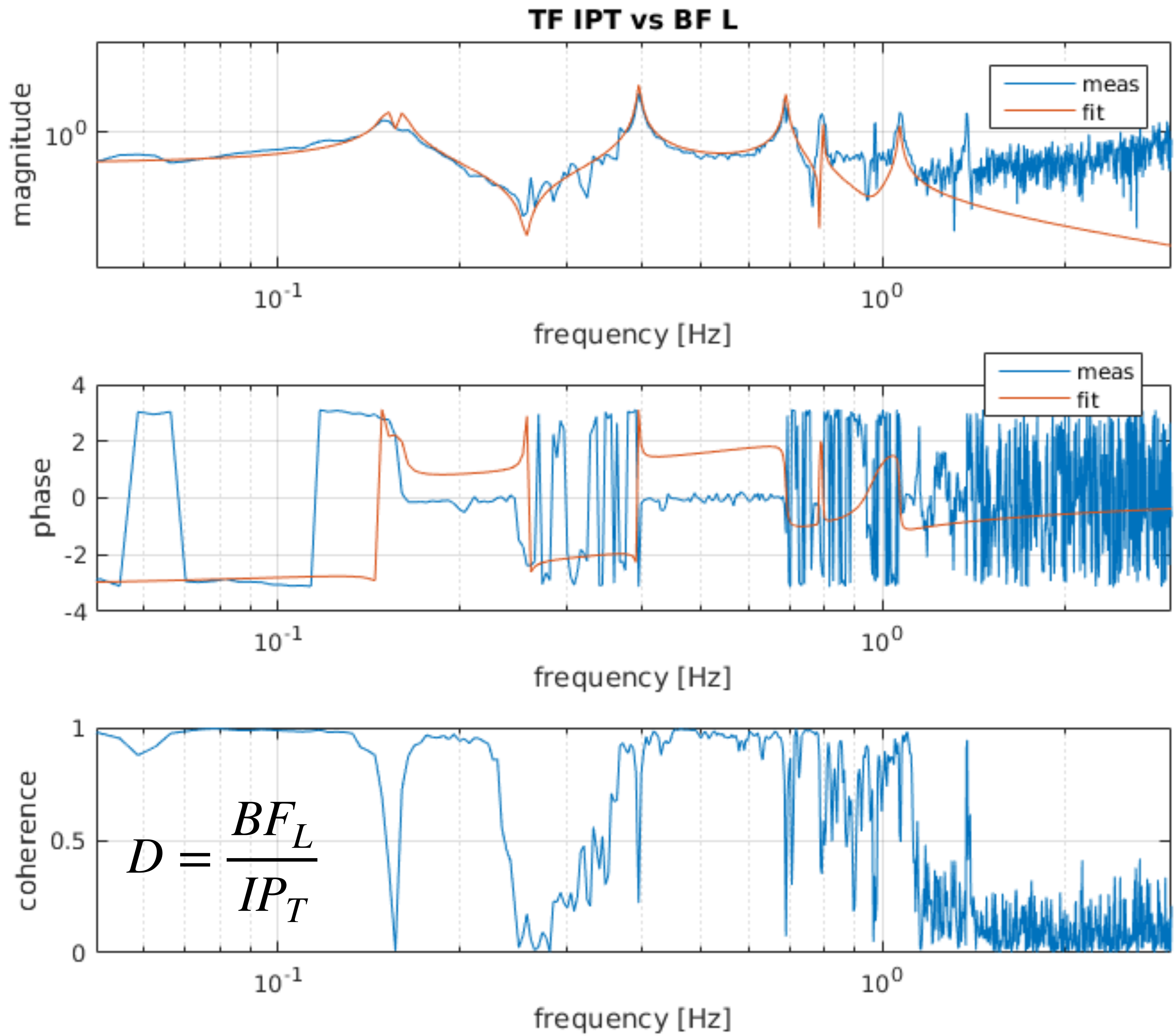
$$D = \frac{TM_P}{IP_L}$$

Inertial damping: residual motion of the bottom stage (V)

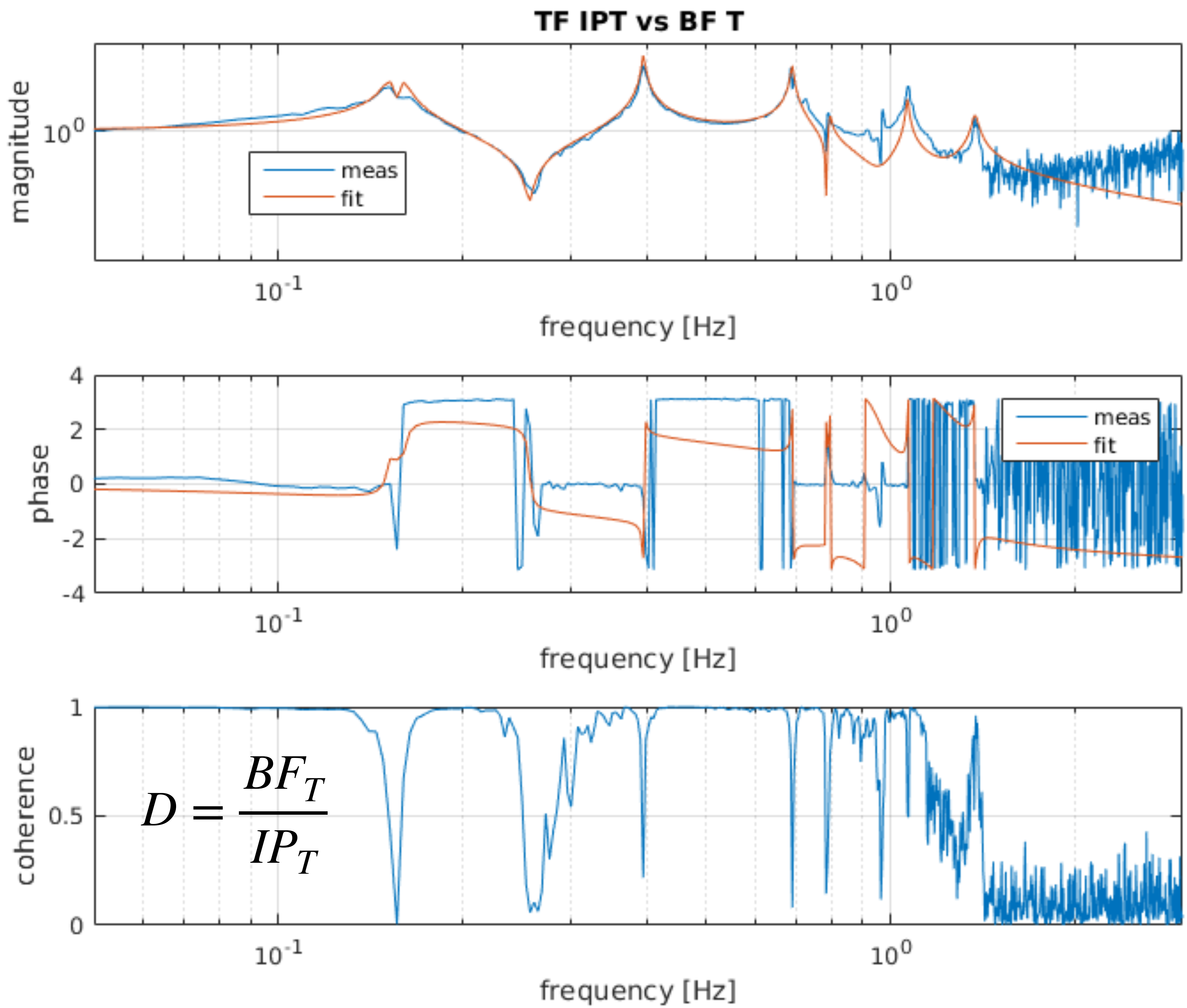


$$D = \frac{TM_Y}{IP_L}$$

Inertial damping: residual motion of the bottom stage (VI)

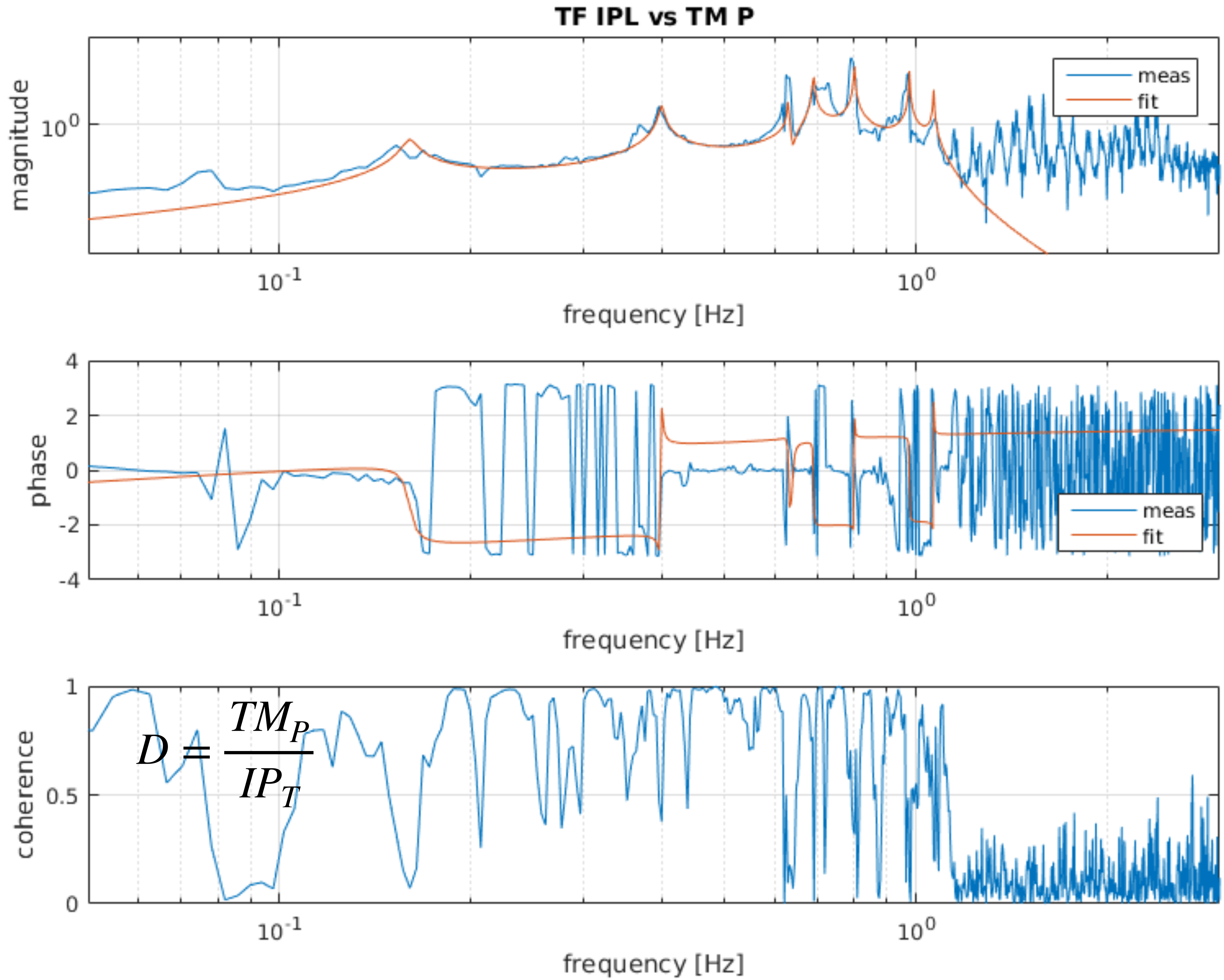


Inertial damping: residual motion of the bottom stage (VII)

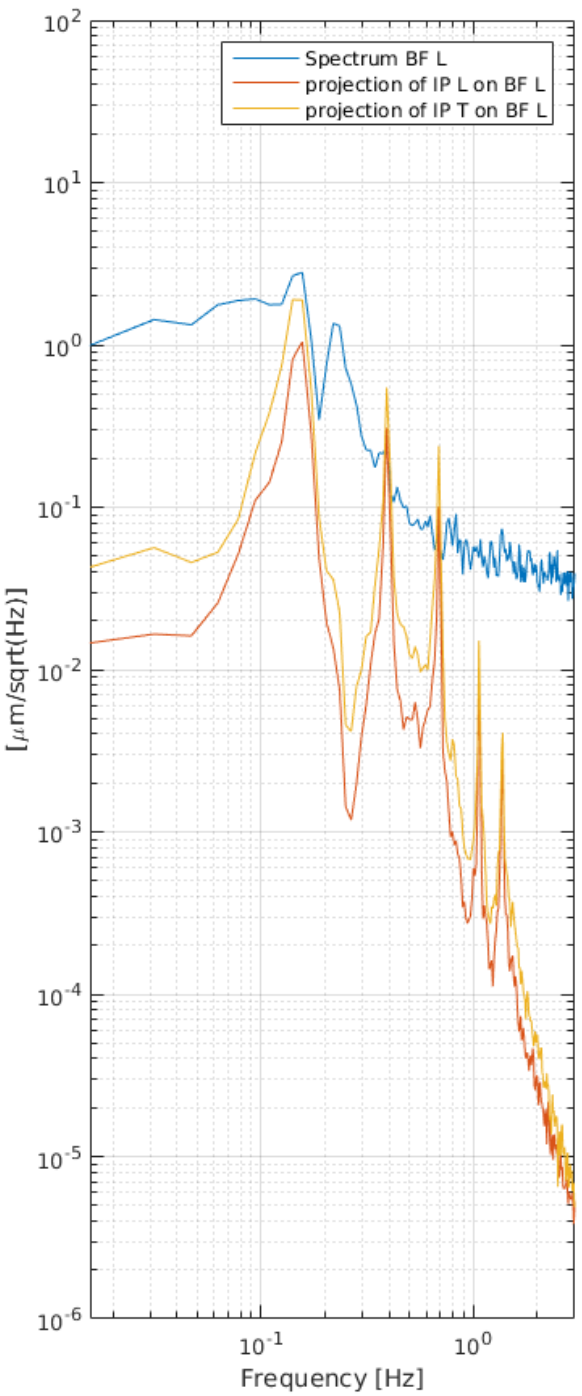


$$D = \frac{BF_T}{IP_T}$$

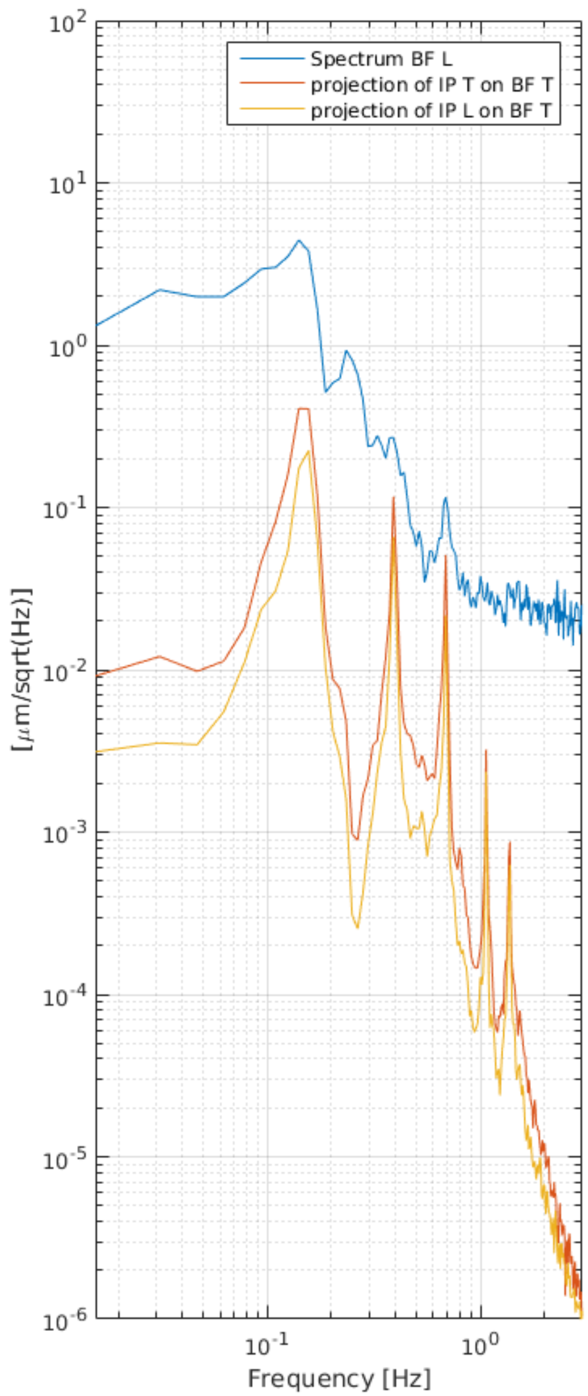
Inertial damping: residual motion of the bottom stage (VIII)



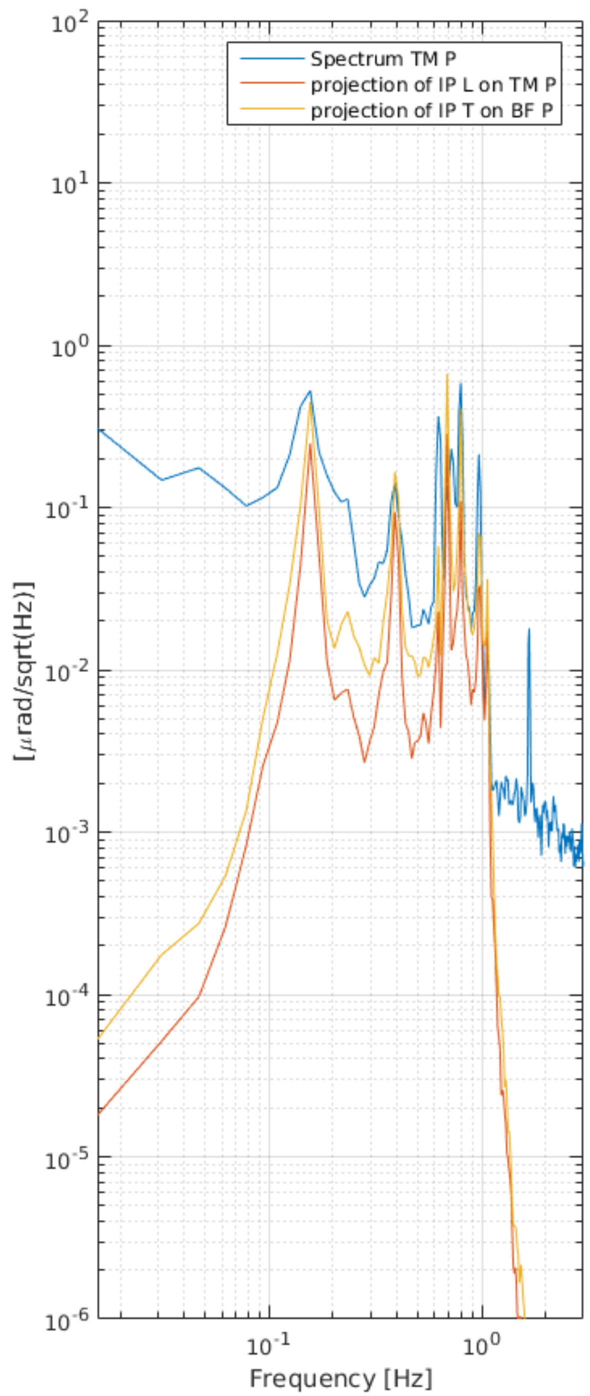
Inertial damping ITMX: residual motion of the bottom stage (IX)



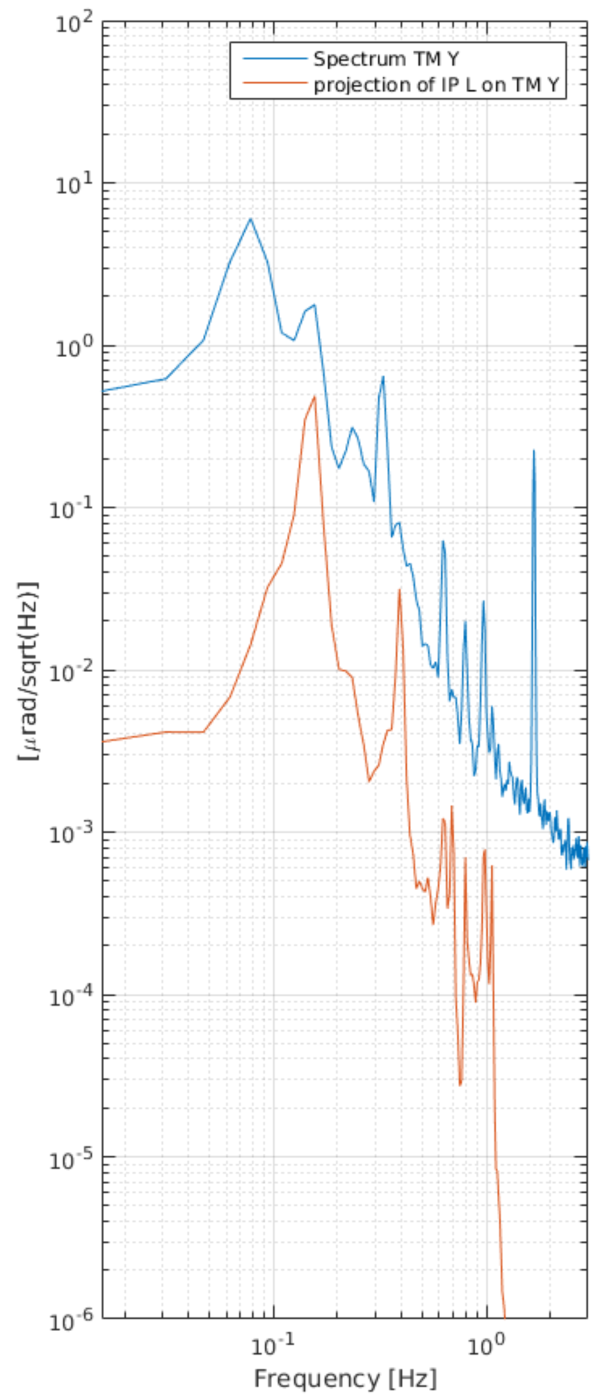
BF L: damp off



BF T: damp off



TM P: damp off



TM Y: damp off

Summary

- We have diagonalized sensors and actuators
  - LVDT → geometrical sensing matrix
  - Coils → readout matrix
  - Inertial sensors → readout sensing matrix
- We have estimated the noise of the sensors
- 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	0,1	
BF	1	1	0,3	
TM			0,8	0,2

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

Conclusion and next steps

- The test on ITMX shows that inertial damping (ID) reduces the test mass motion more than the position control with only LVDTs
- Some work to further optimize the ID (e.g move the blending frequency to 70 mHz) is going on
- To evaluate its impact, a comparison of the lock performances with and without ID would be interesting
- Do we need ID on all the type A suspension? If the answer is YES some actions have to be taken:
  - Fix the accelerometers noise on ITMY
  - Carefully evaluate the geophones noise performance: is it really possible to use them? Should we consider to replace them with accelerometers?

Thanks for your attention!