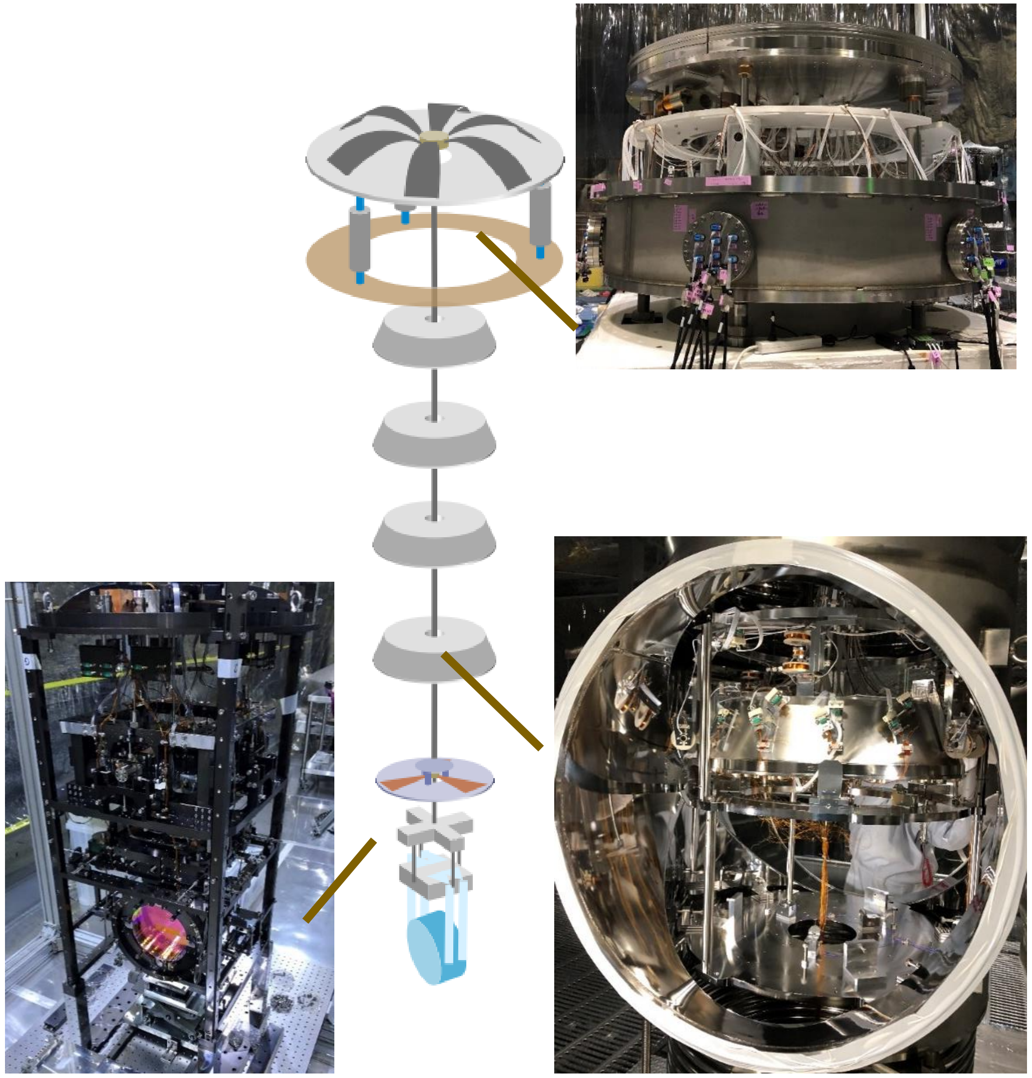
Fast localization of coalescing binaries with gravitational wave detectors and

Low frequency vibration isolation for KAGRA



Yoshinori Fujii (U. of Tokyo, NAOJ)

KAGRA F2F meeting

Thesis contents

1. Introduction
2. Benefit of adding detectors to the observation network
   Fast localization simulation with one template search in hierarchical approach using HLVK-network [ref HLV]
3. Low frequency vibration isolation
4. KAGRA seismic Attenuation system
5. Suspension control design

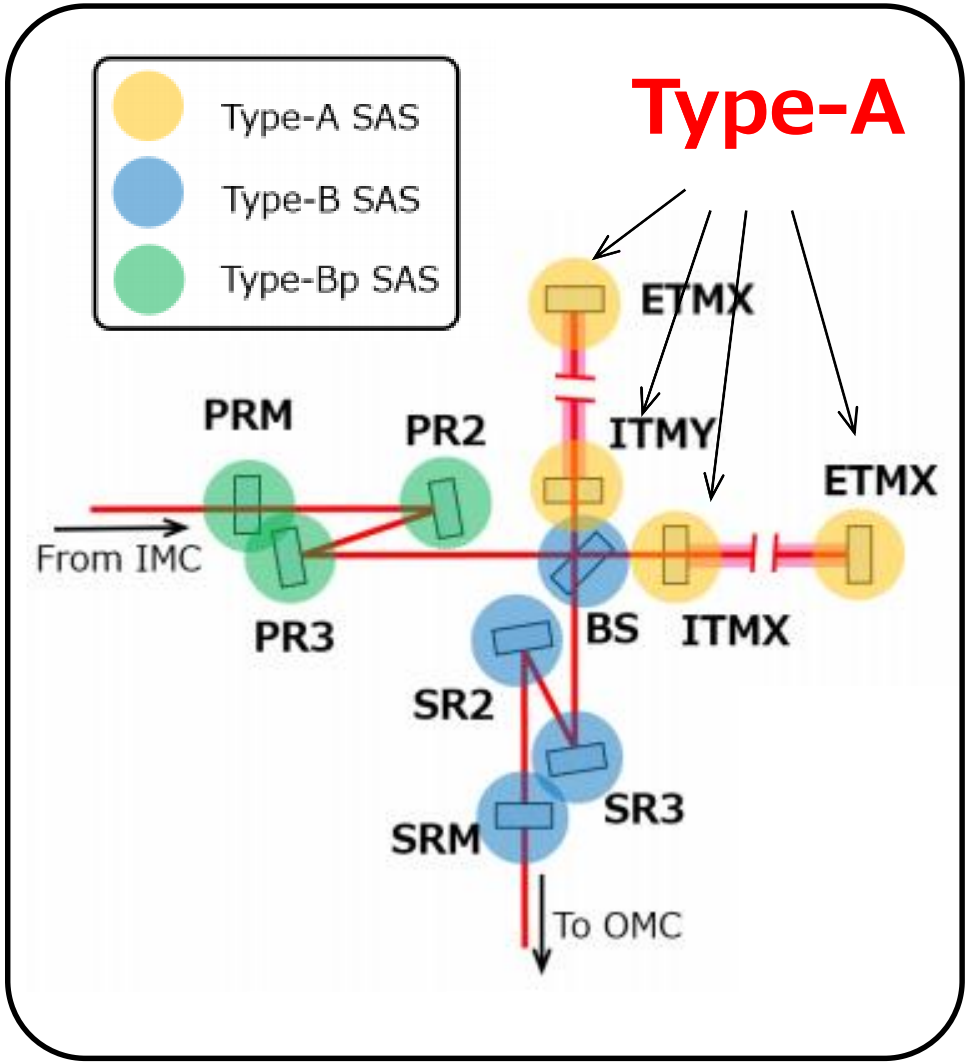
Today's topic

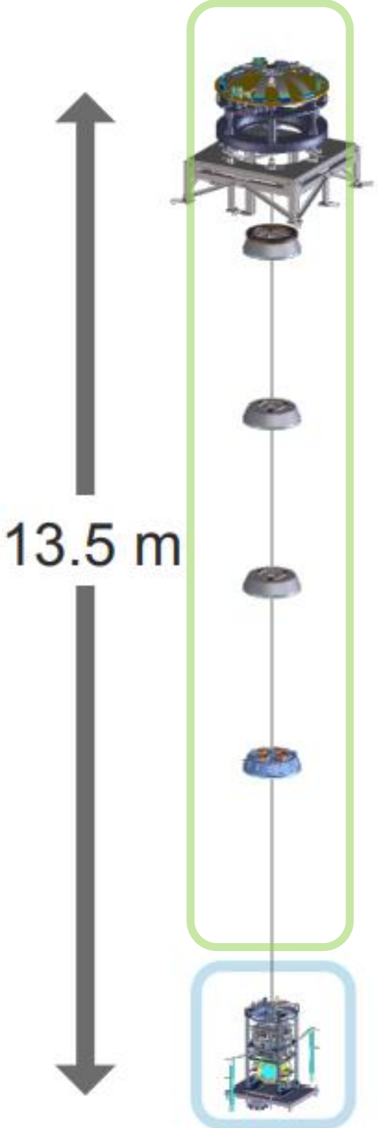
6. Performance test of local control for KAGRA Type-A suspension

7. Summary

→ TypeA suspension & Controls toward lock acquisition

Before starting, What's Type-A?



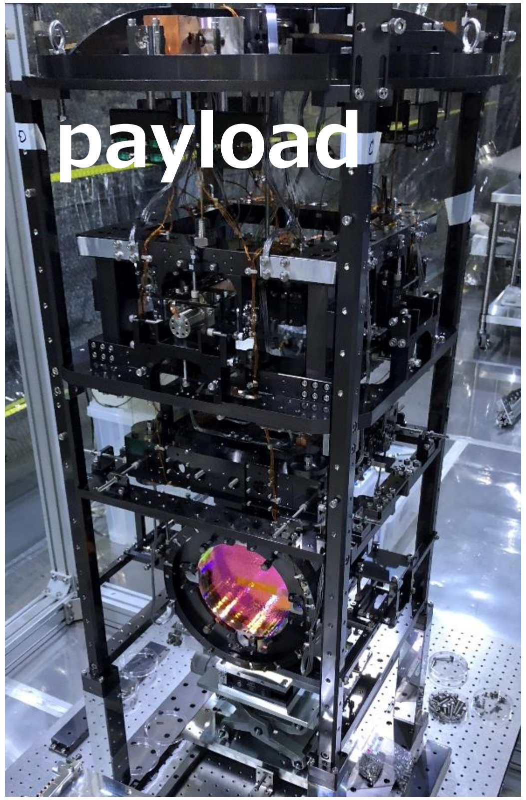


→ **The longest suspension in KAGRA**

- Upper 5 stages: room-temperature
- Lower 4 stages: cryogenic-temperature

And, Type-A has cryogenic part

Inside cryostat



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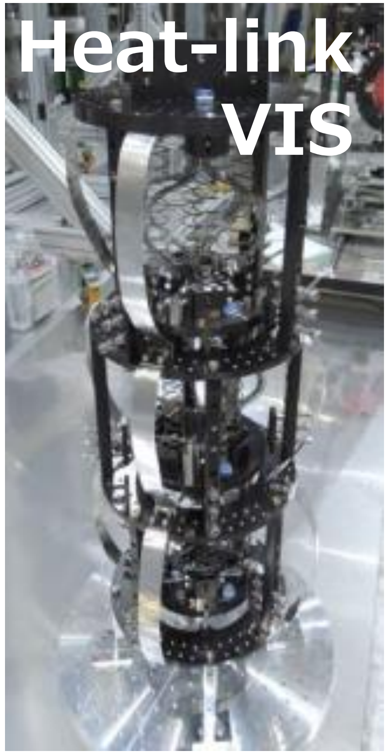
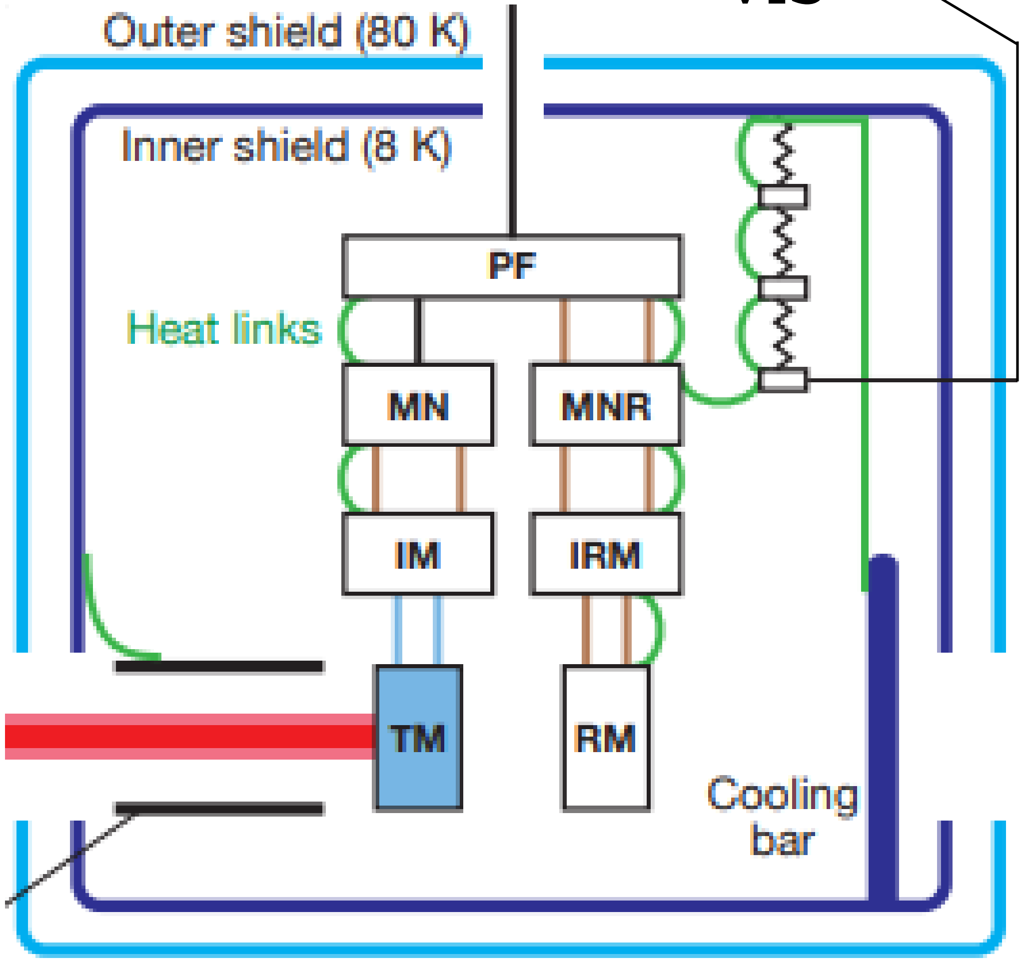


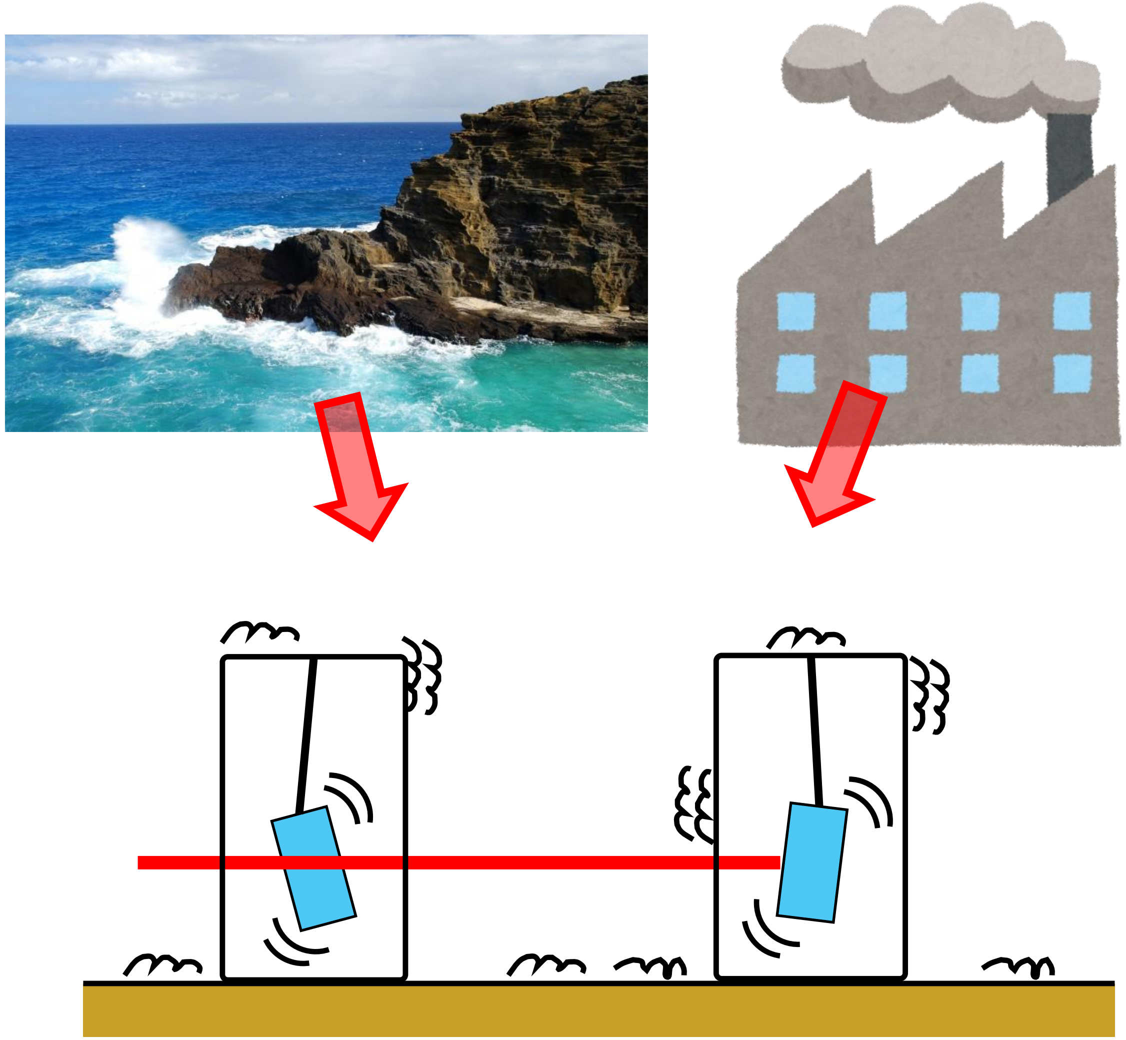
(+ Wide-angle baffle)

Heat-link
VIS

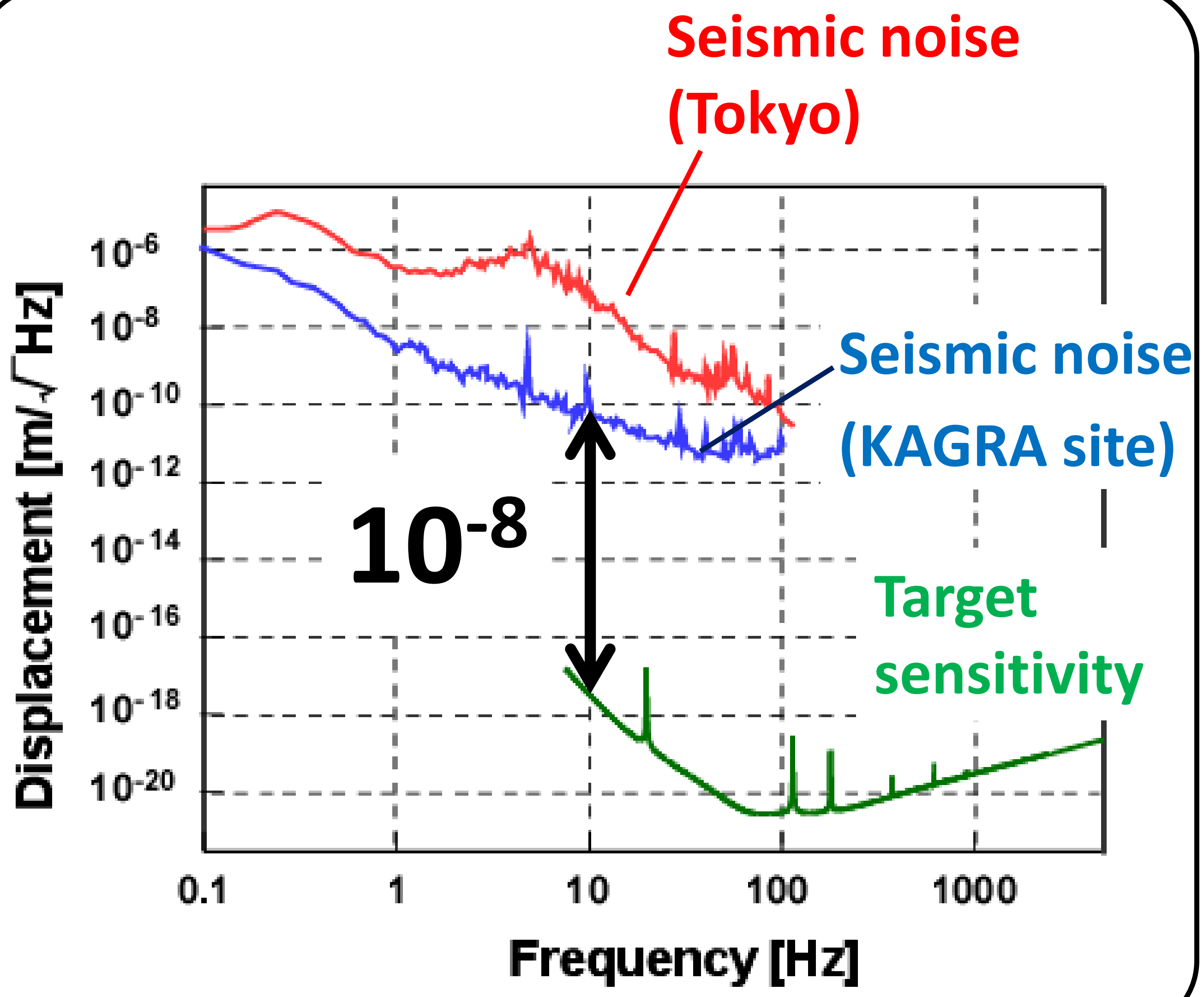


JGW-P1809347

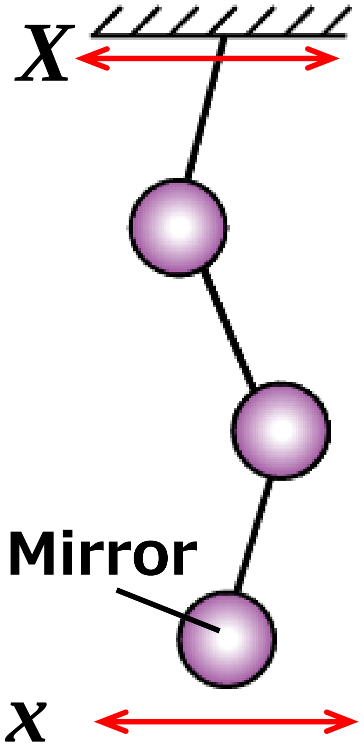
Why pendulum?

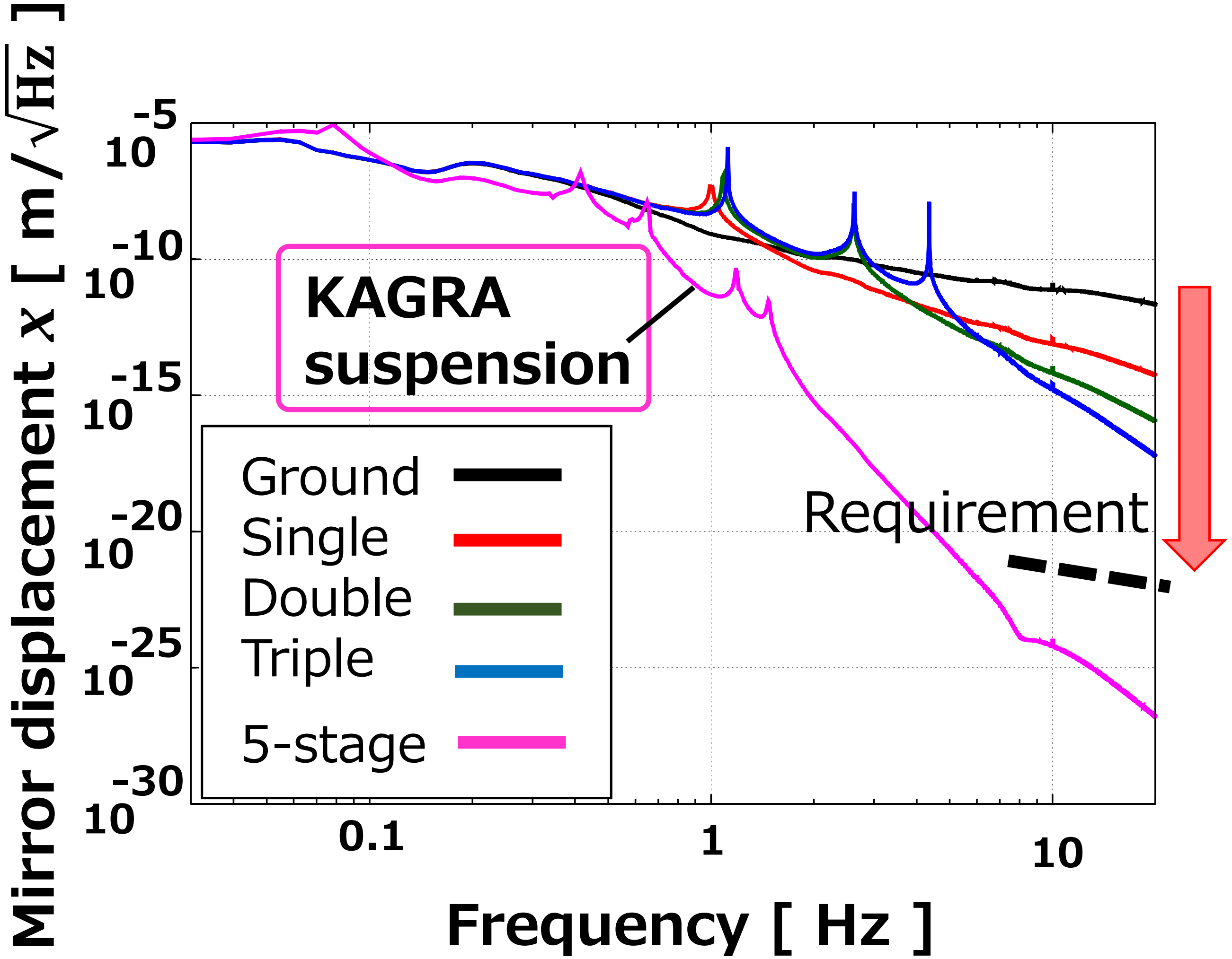


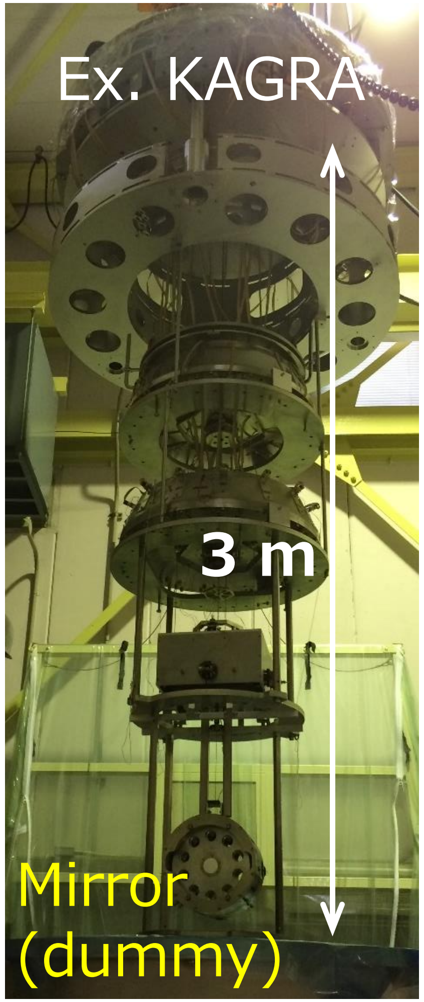
→ To treat seismic noise



Seismic noise attenuation → pendulum





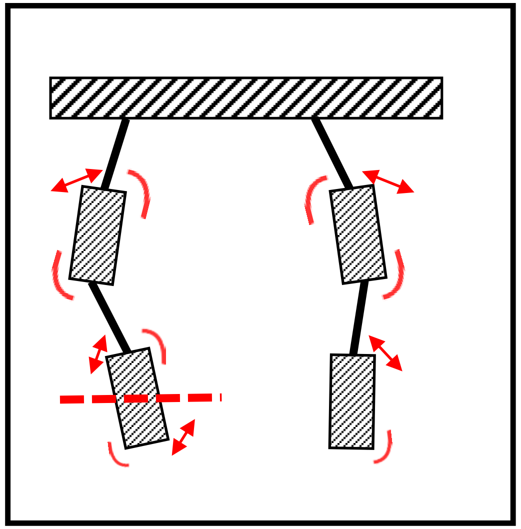


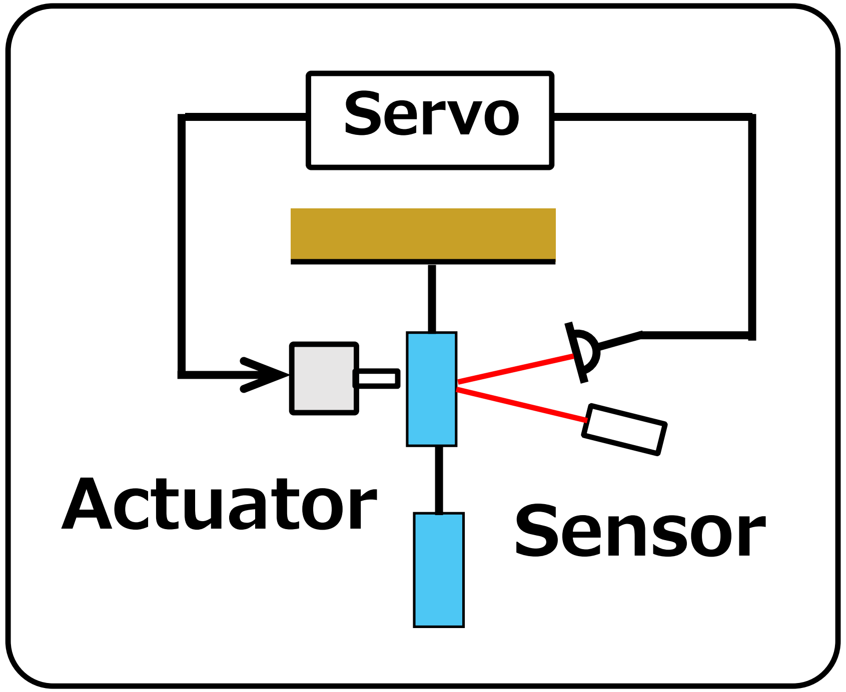
(BS/SRs-suspension case)

Resonant damping / Mirror Alignment: necessary

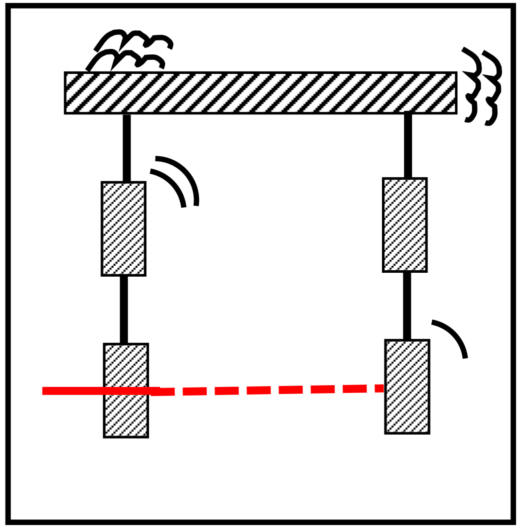
→ Control system

~~interferometer operation~~





Stable operation

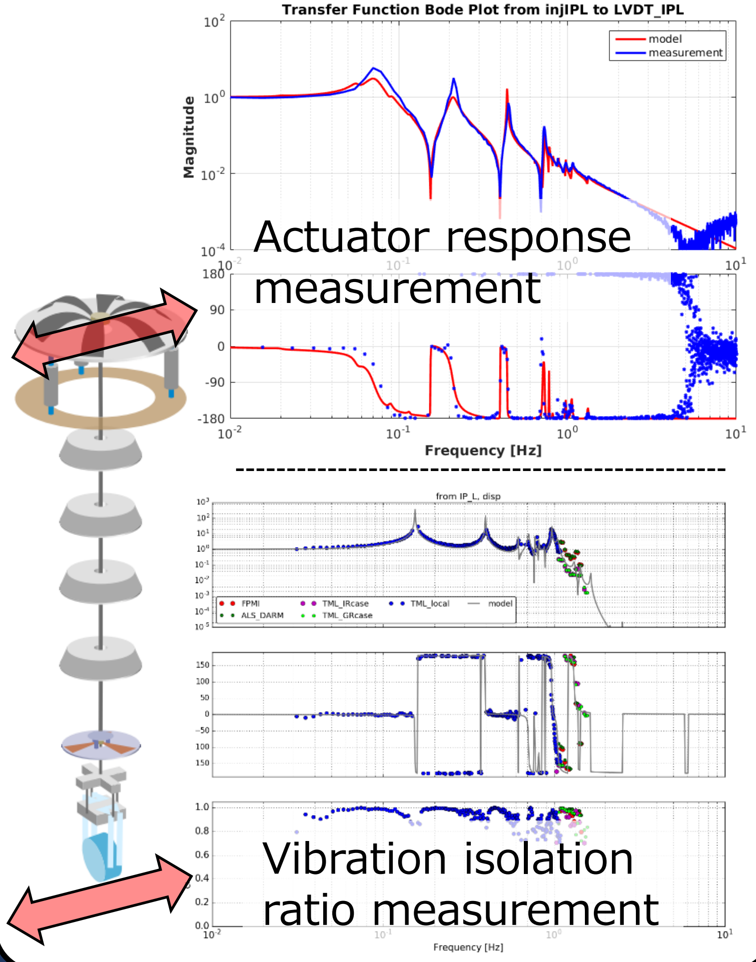


* DAMP resonances.
* Don't care the controls noise.

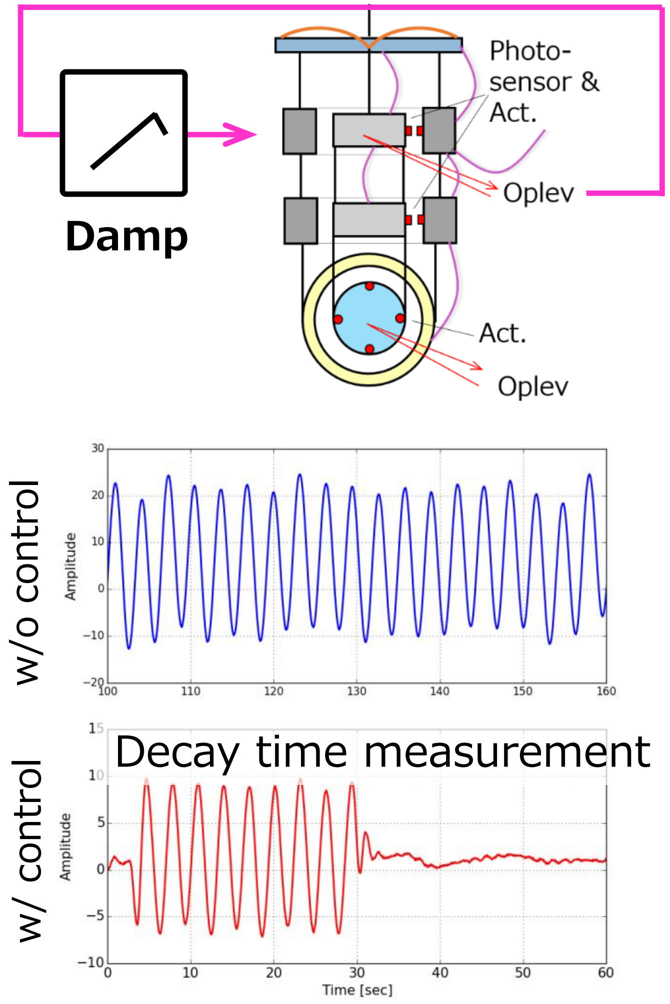
* Freeze the mirror
* Keep low noise

My work: Constructing controls toward interferometer lock

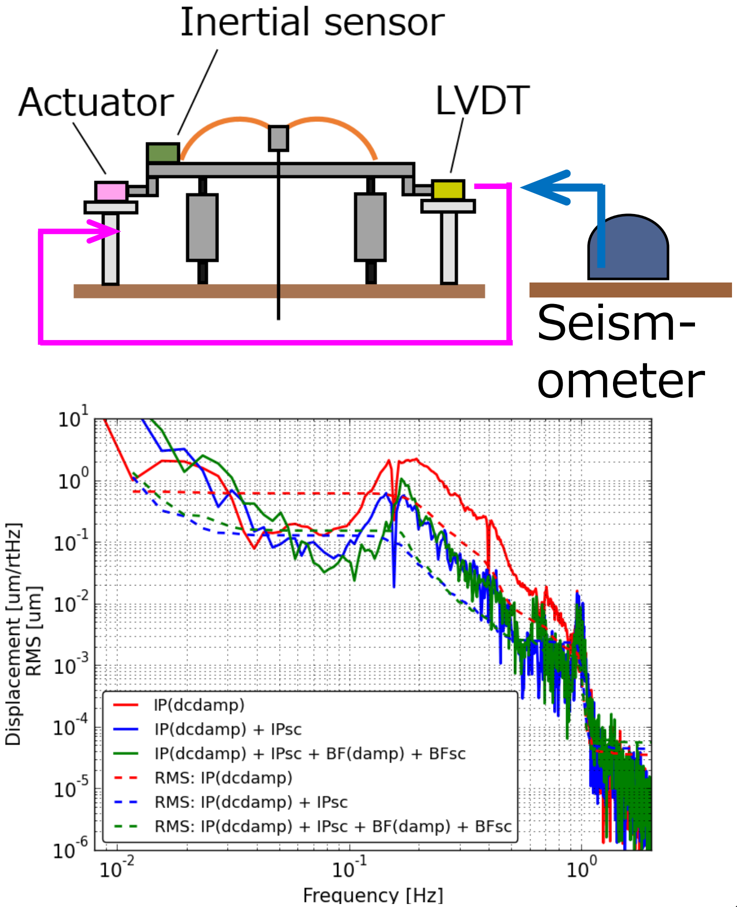
1. Mechanical system characterization



2. Resonance damping

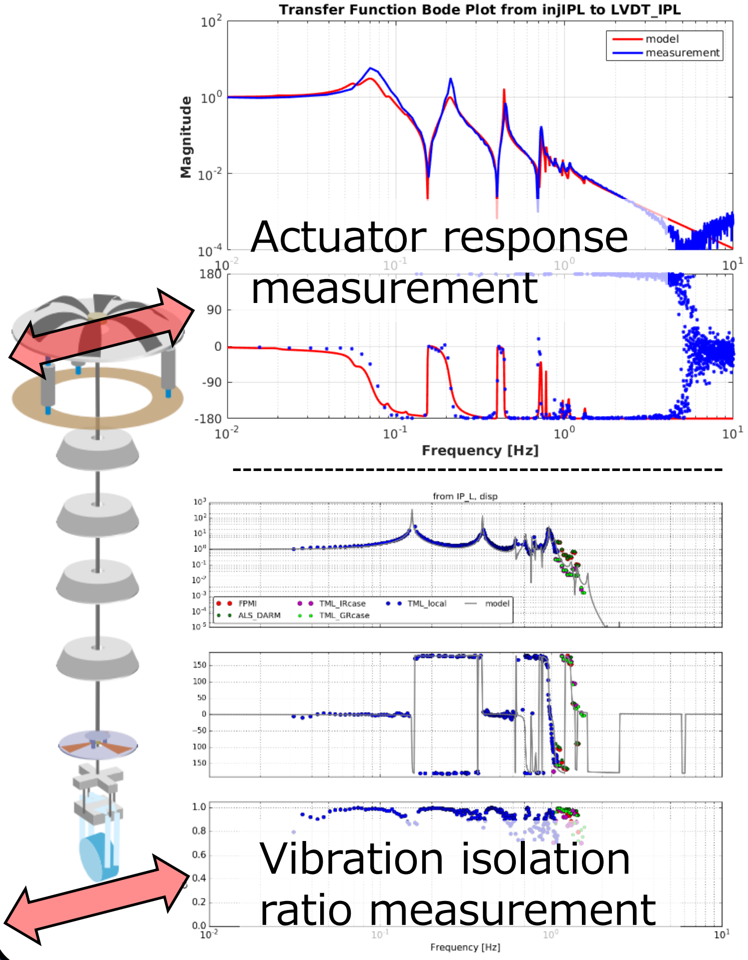


3. Mirror residual suppression

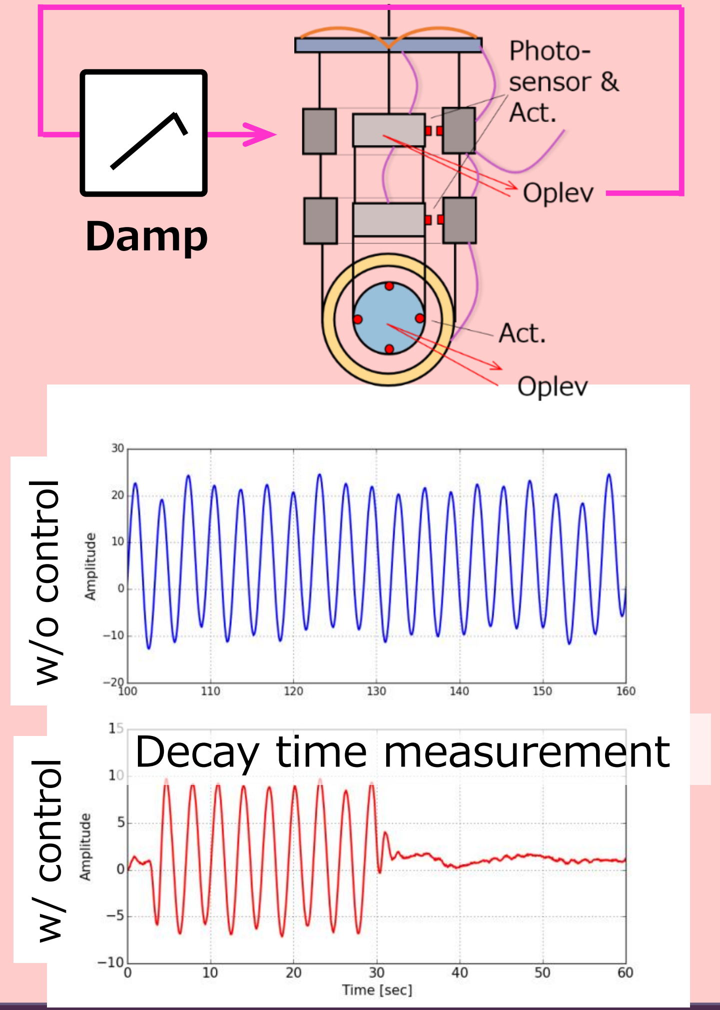


My work: Constructing controls toward interferometer lock

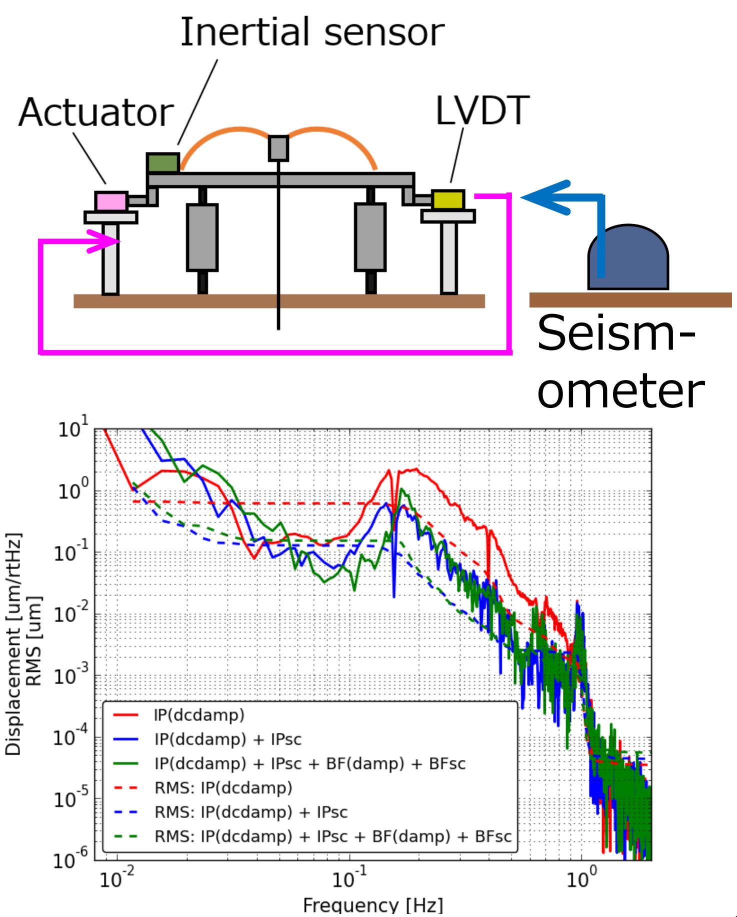
1. Mechanical system characterization



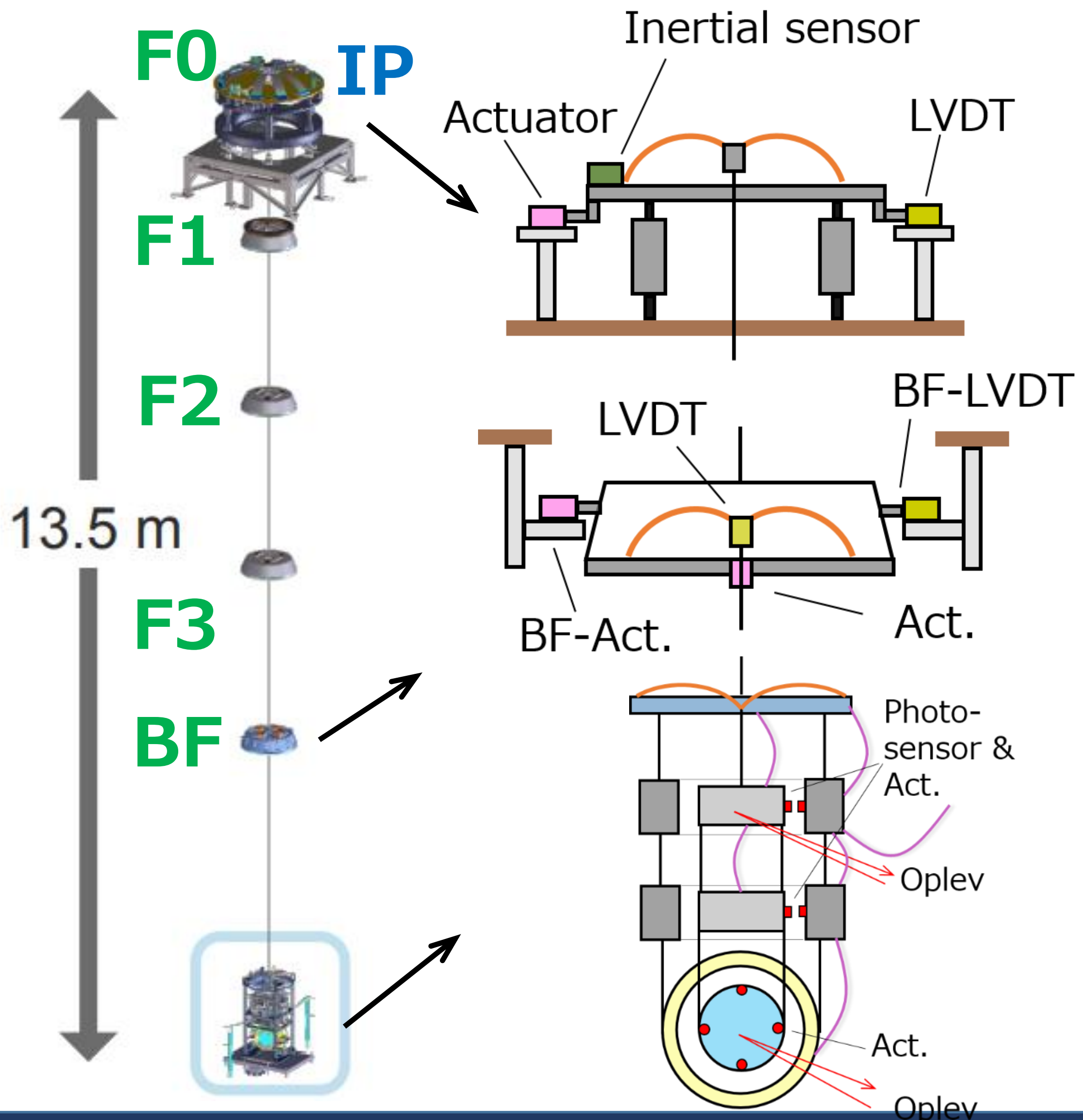
2. Resonance damping



3. Mirror residual suppression



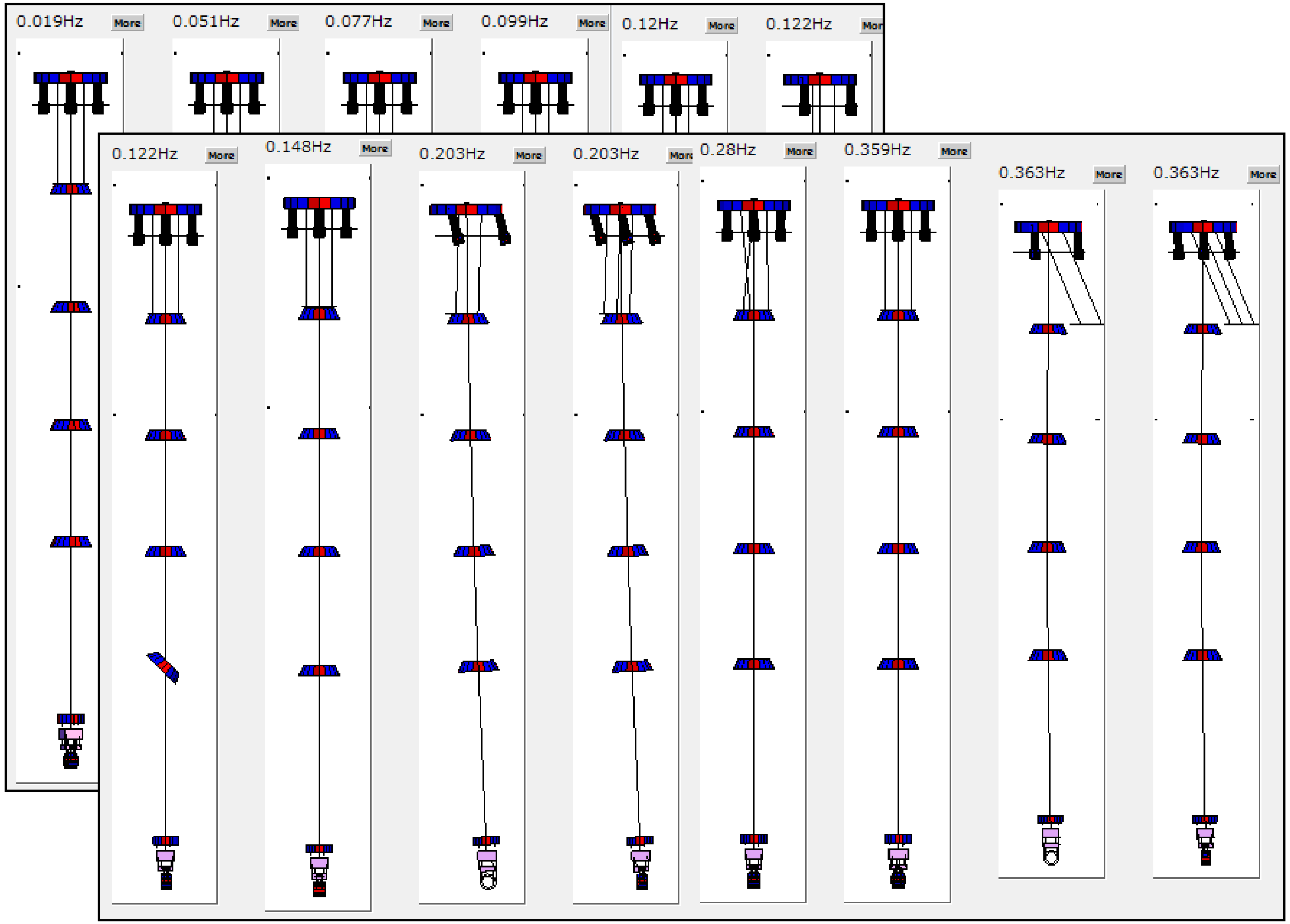
Control system for damping

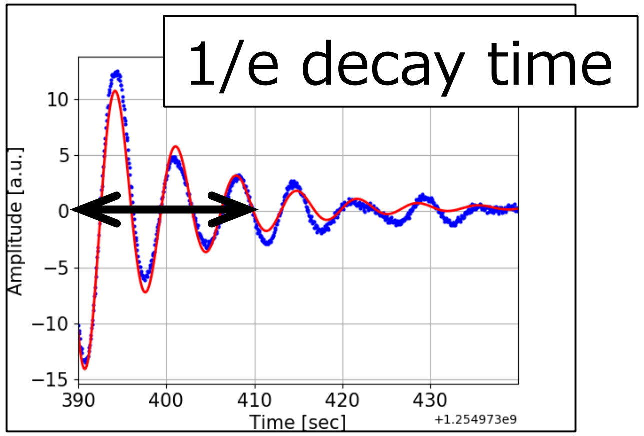


Tower part:
* controlled at each stage
* DC or (DC+damping) control

Cryogenic payload part:
* Actuated at IM(+MN) stages
* Mainly optical levers are used.
* Most of nuisance RM-chain modes
→ Finely tuned band-pass filters

Target: **Damp all the resonances which disturbs the lock acquisition, within 1min.**

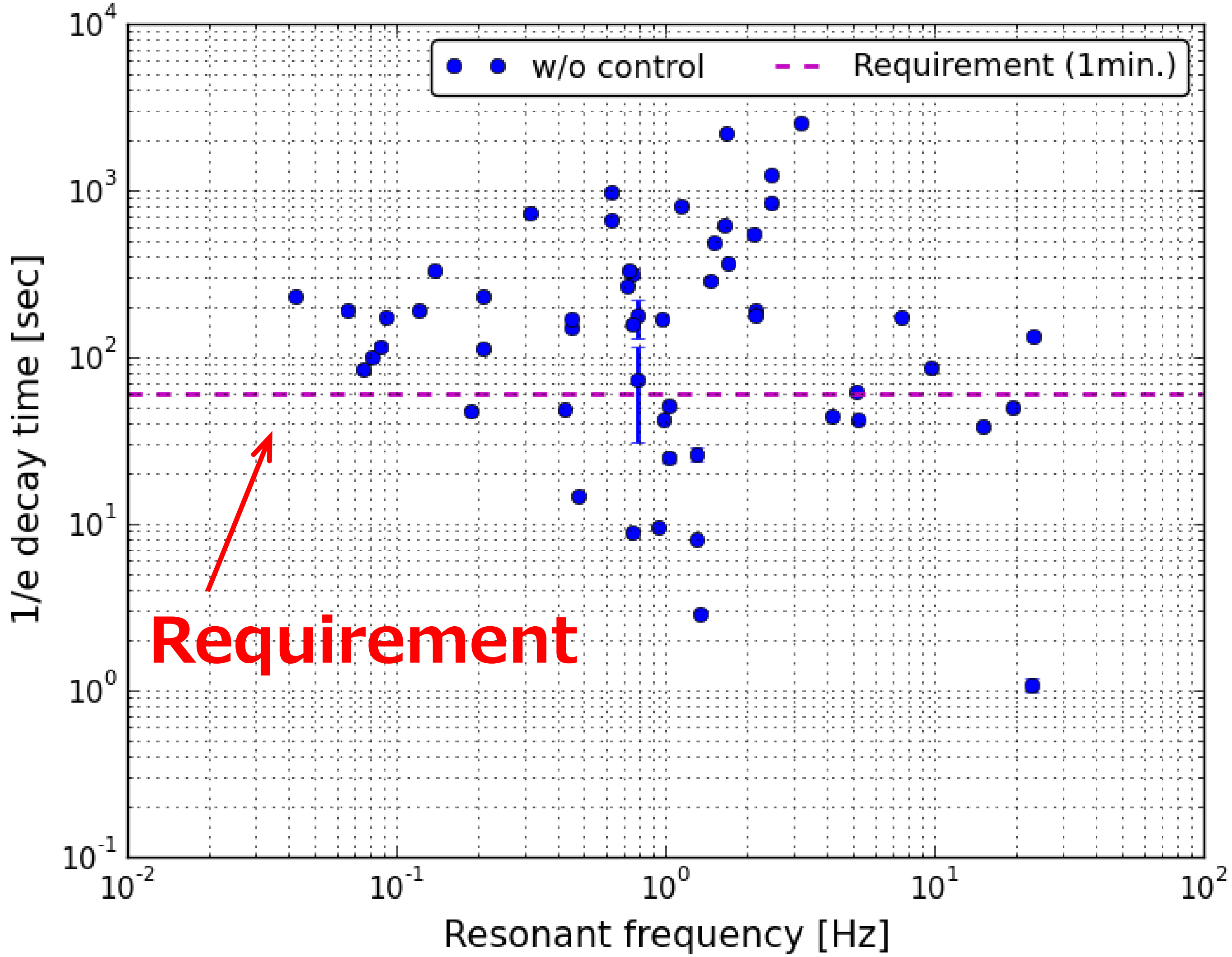




Assuming rigid-bodies
→ 75 modes

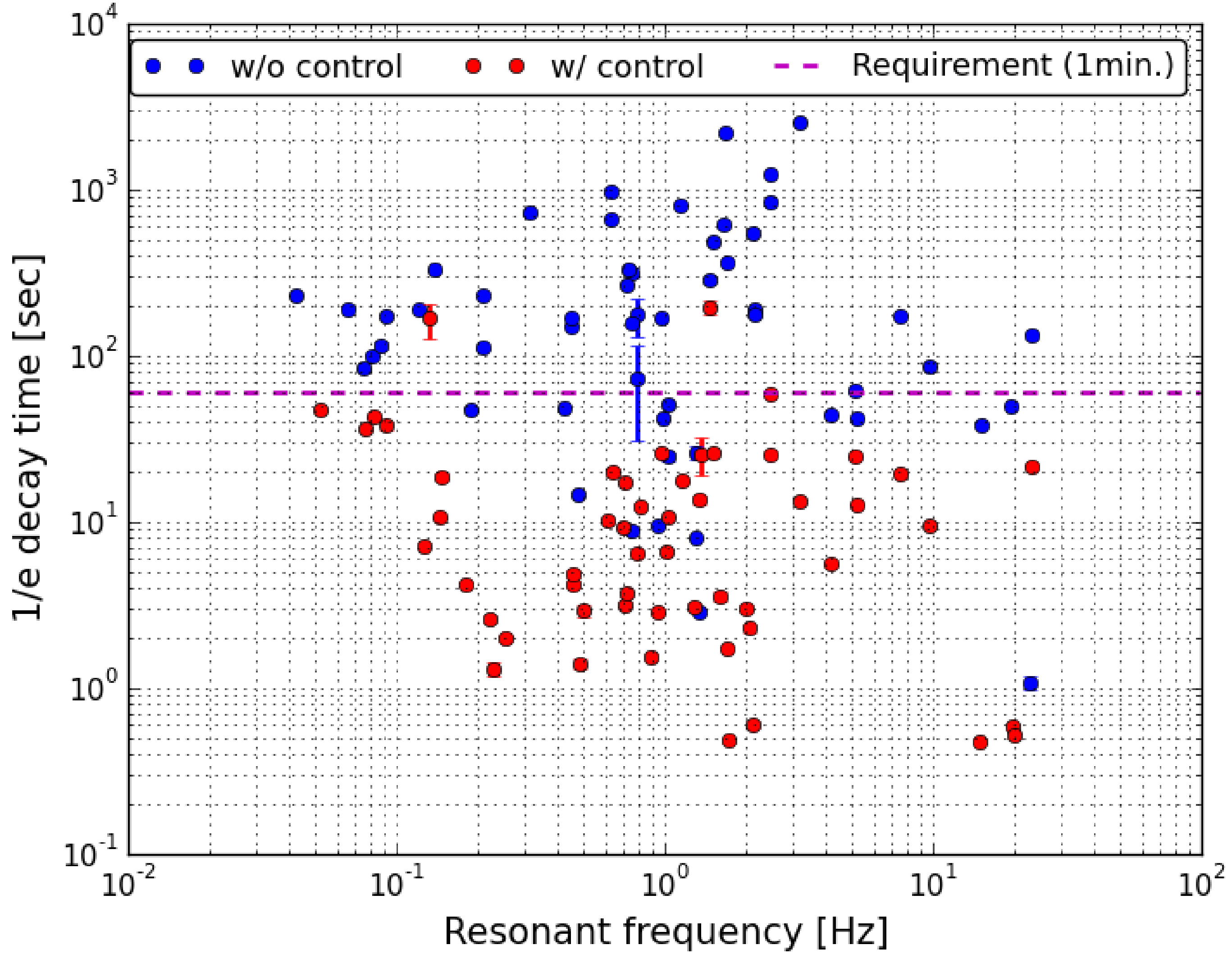
Measureable:
→ For 53 modes

Result: resonant frequency vs. decay time



w/o control

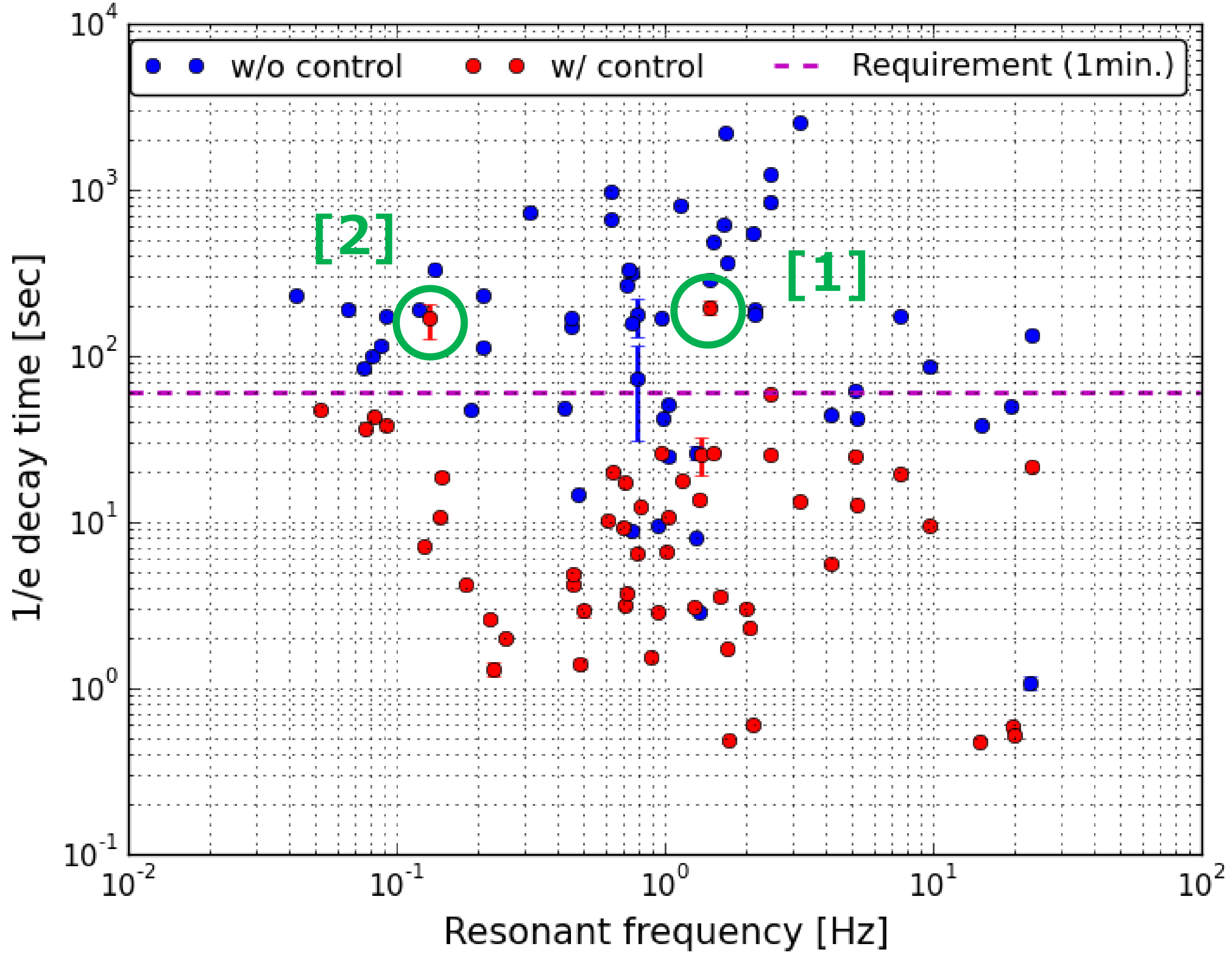
Result: resonant frequency vs. decay time



w/o control

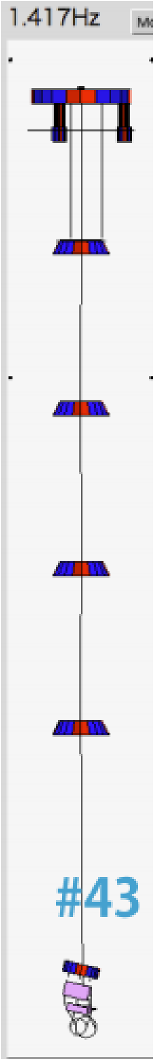
w/ control

Result: resonant frequency vs. decay time



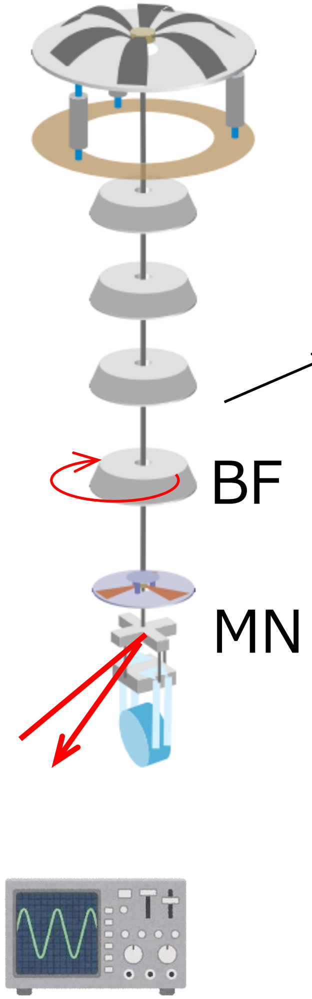
[1] #43: **1.5Hz**
Roll / Trans. motion
→ Not disturbed the lock acquisition.

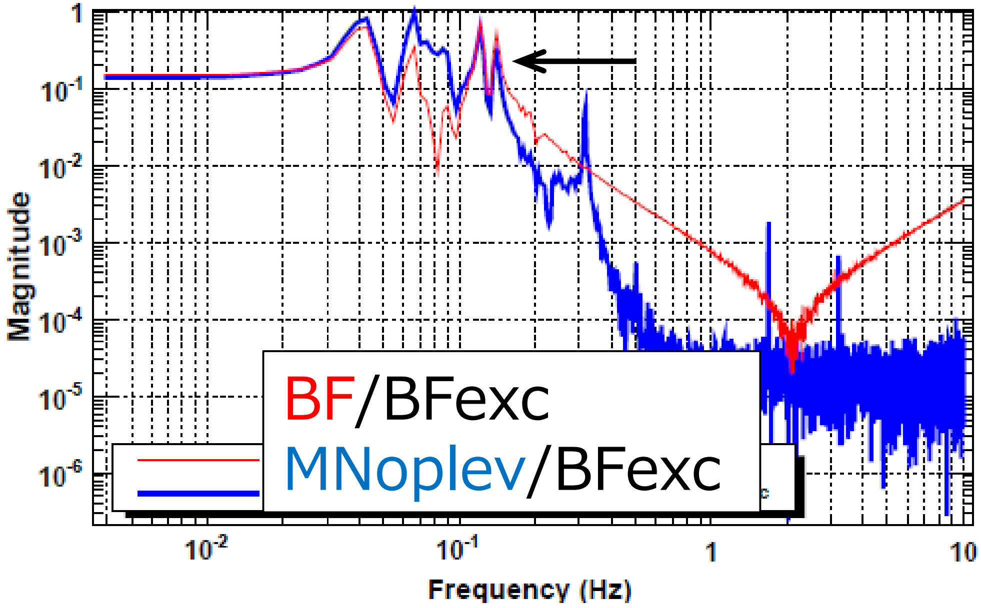
[2] 0.14Hz
unknown Yaw motion
→ failed to predict w/ the model w/o heat-link system.
→ visible at BF-stage, not effectively damped w/ BF-stage.

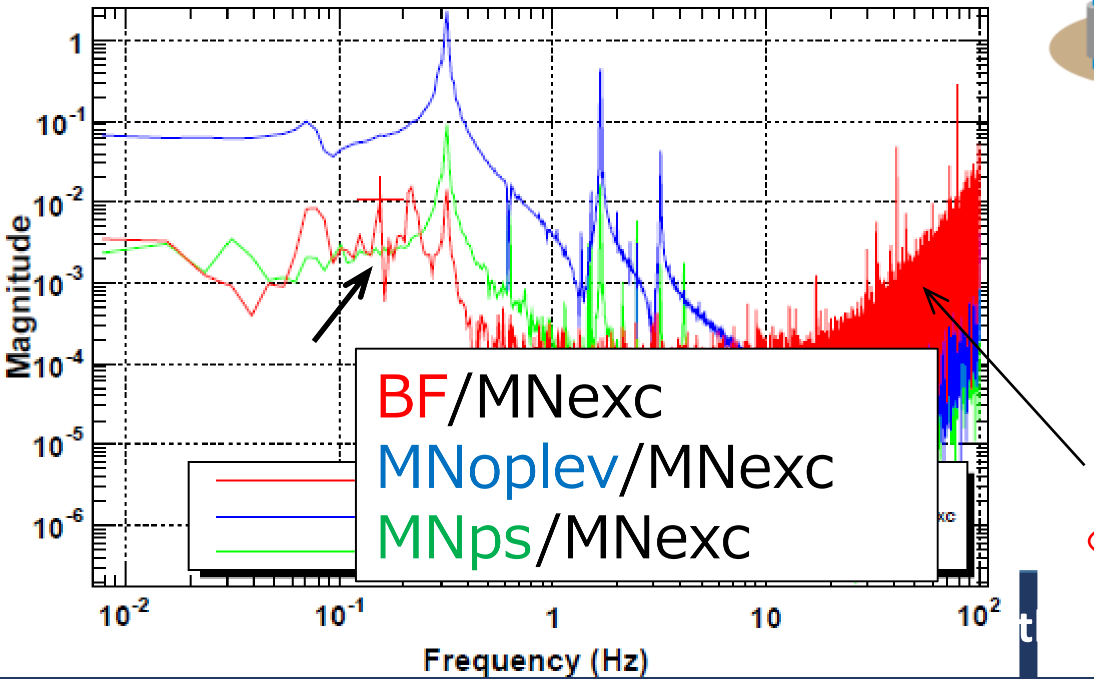


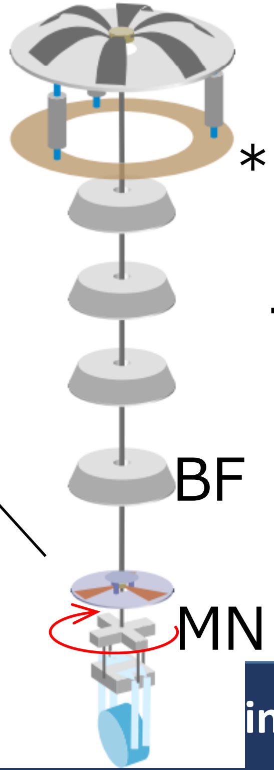
Reference mode list: https://gwdoc.icrr.u-tokyo.ac.jp/DocDB/0078/G1807866/001/sumconTypeA20161114.pdf

So, is this unknown Yaw mode problematic?









* When white noise injected at BF-stage:
→ The mode looks exited.

* When white noise injected at MN-stage:
→ Not (clearly) exited in TM-chain.

* The decay time ~3min.

→ Not problematic for (current) lock-recovery.

Summary (for damping resonances):

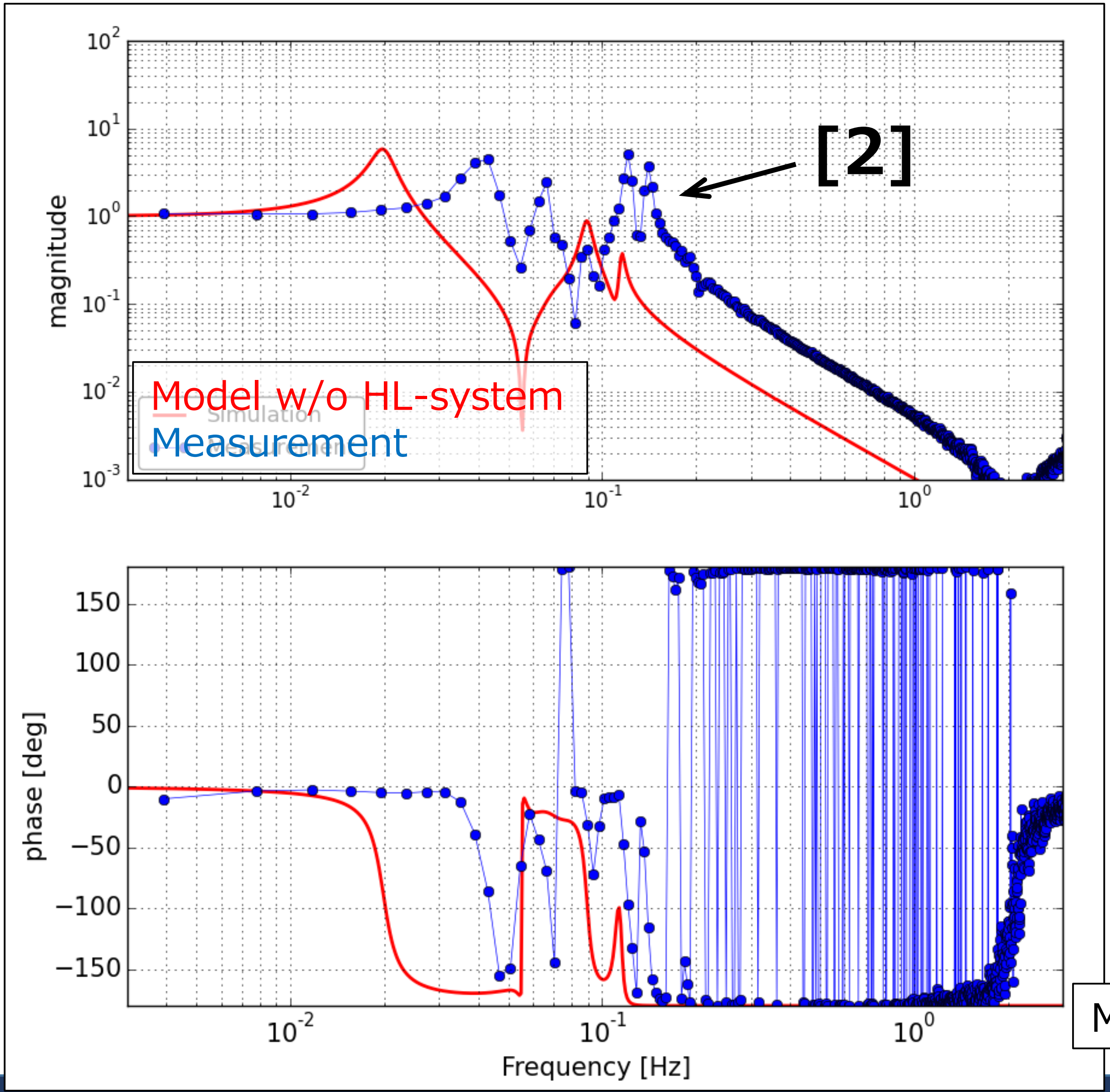
-- The installed damping control system damped all the resonances which disturbs the lock acquisition **for the lock-recovery mode**.

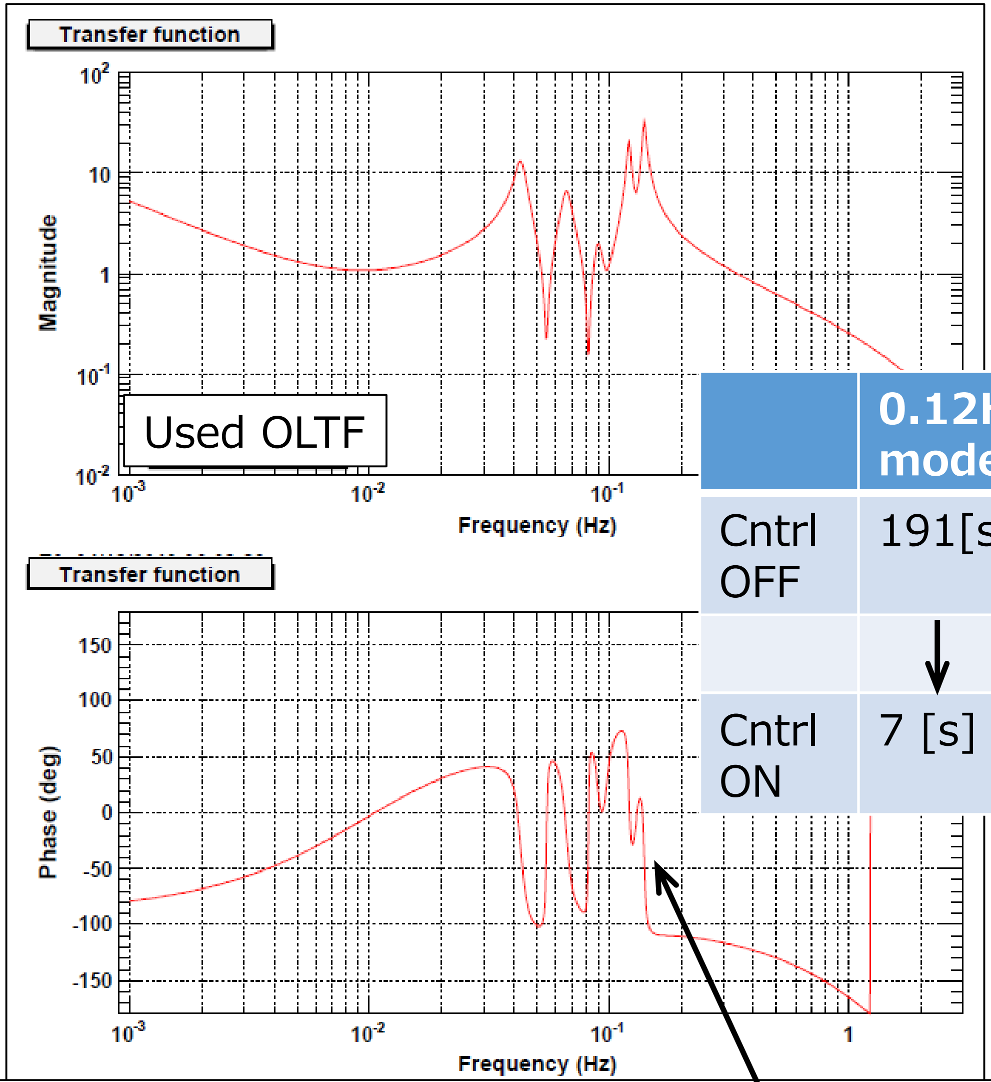
-- exception: one mode
  -- This mode looks from HL-system
  -- This would be problematic when upper stages are used for the global controls. → Further improvement

-- In this work, the payload damping system is constructed mainly with the optical levers (relatively small linear range).
-- better to utilize Photo-sensors more effectively.

Other notes

unknown Yaw mode [2]?



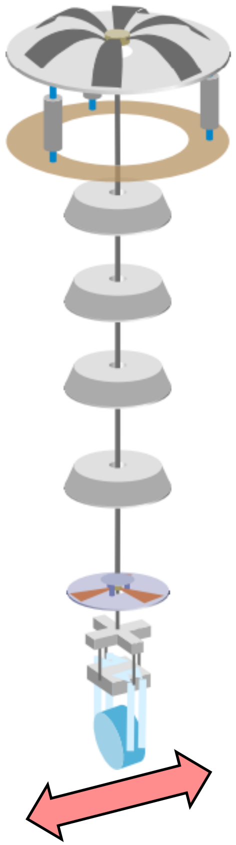


	0.12Hz mode	0.14Hz mode
Cntrl OFF	191[s]	330 [s]
	↓	↓
Cntrl ON	7 [s]	180 [s]

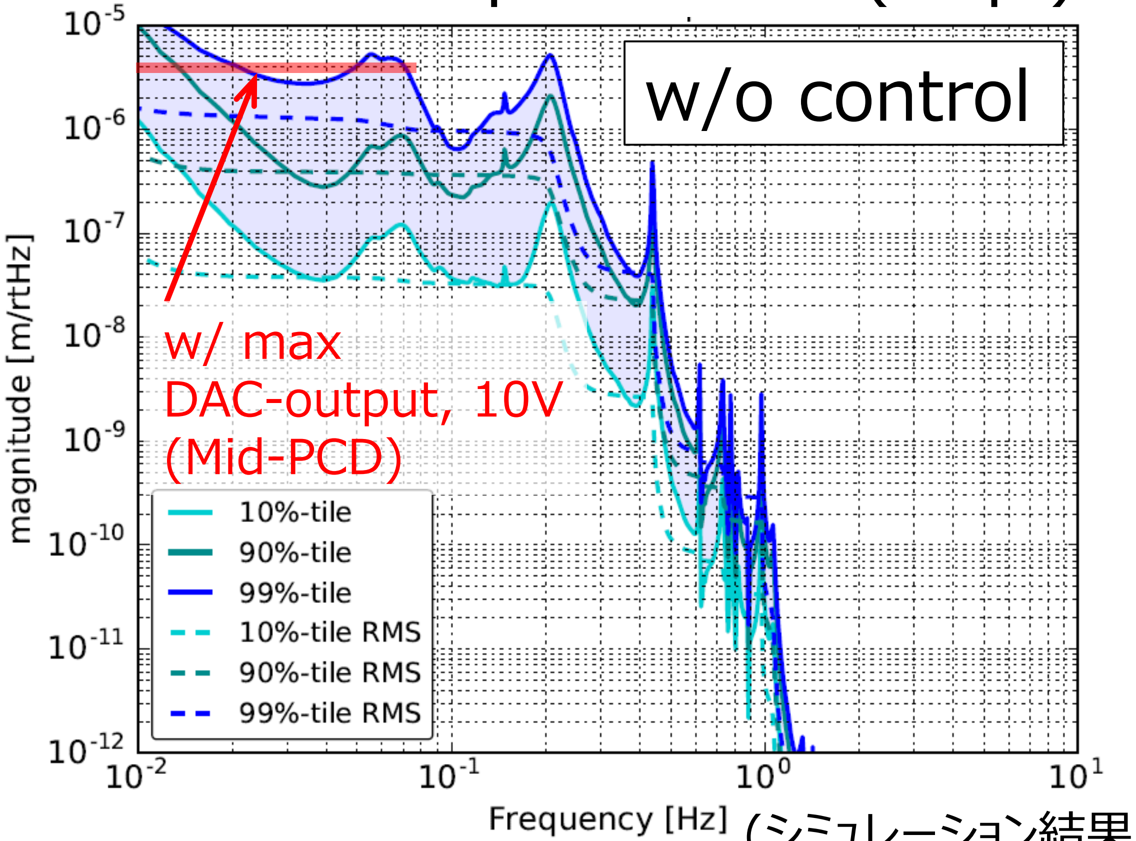
More finely tuned phase compensation might work

Notes: RMS suppression

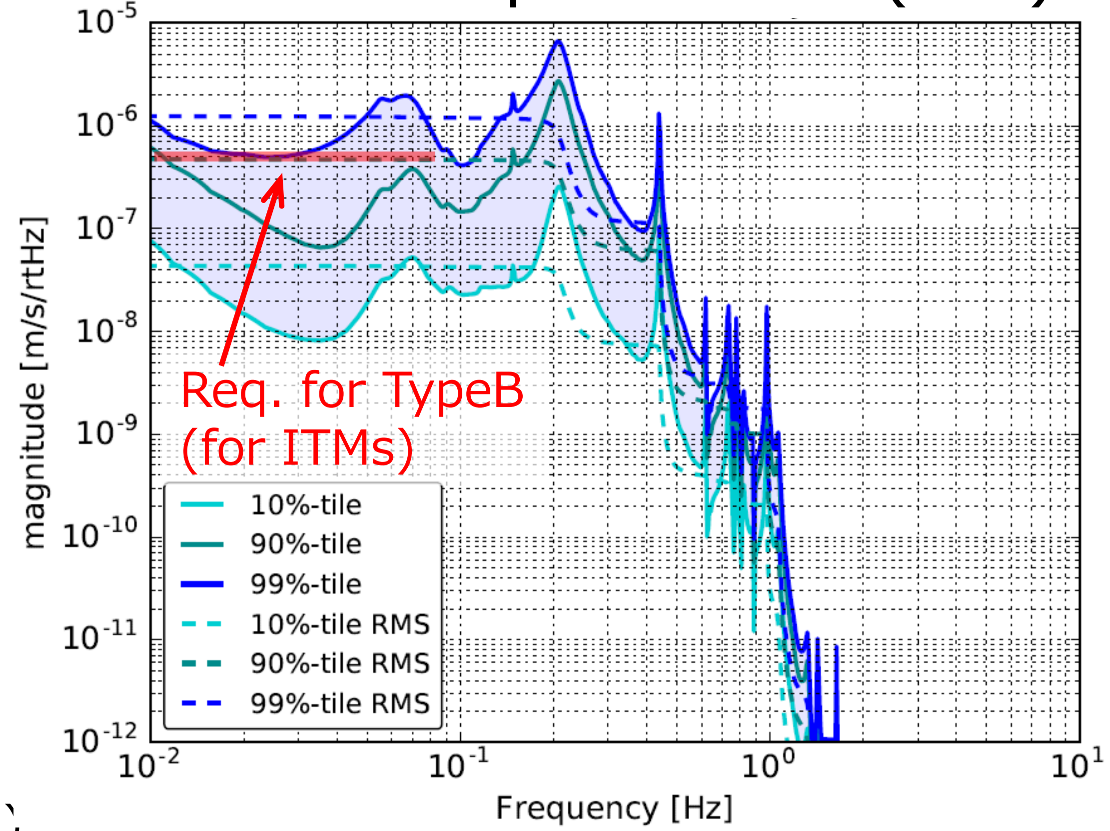
Ground motion and suspension response at KAGRA



Mirror Displacement (disp.)



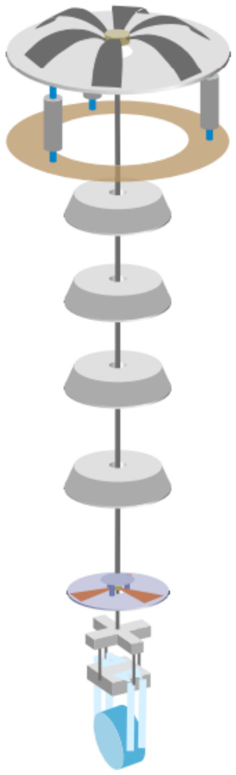
Mirror Displacement (vel.)



(シミュレーション結果)

Ref: https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=10436

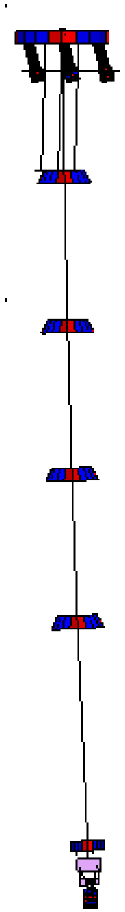
神岡での地面振動レベルと、サスペンションの応答



-- 好天候時
→ 要求値を満たせる

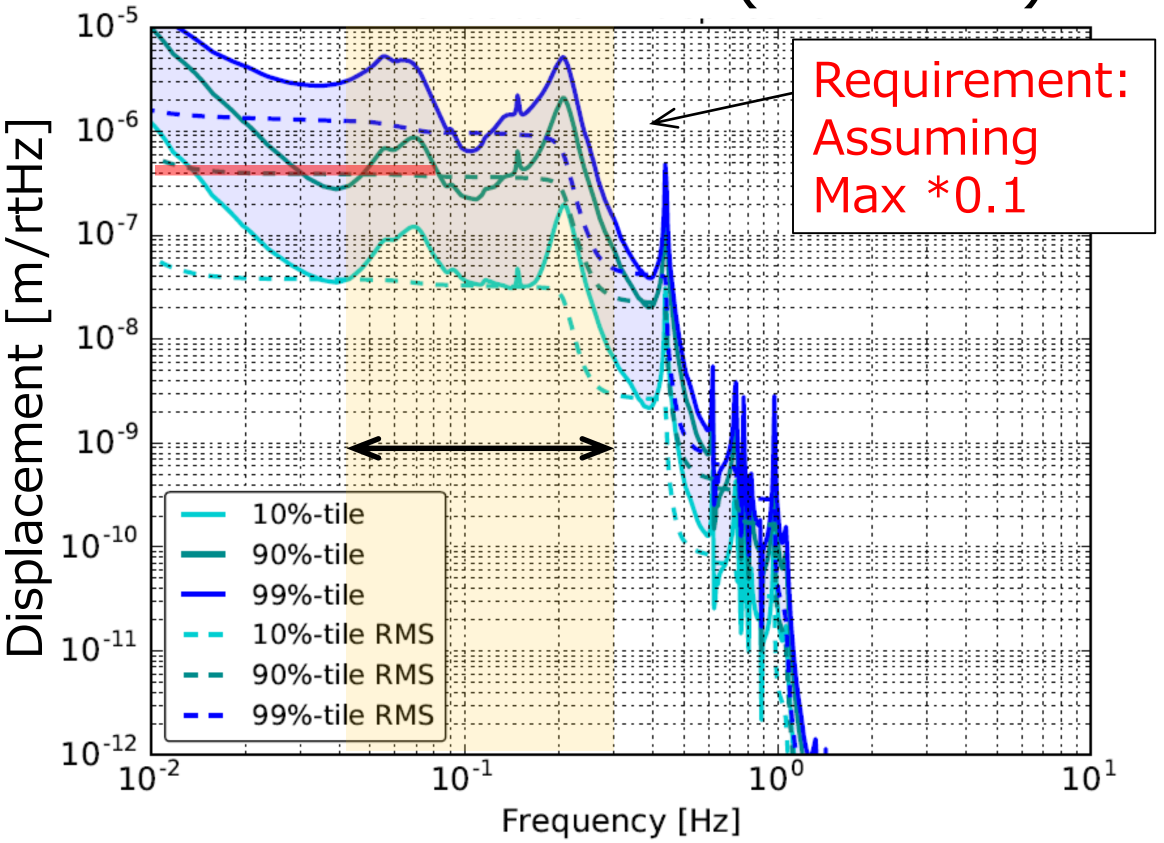
-- 悪天候時(特に冬場)
→ 要対処 at 上段

- RMSの寄与が大
→ 抑制が必要
→ at 上段

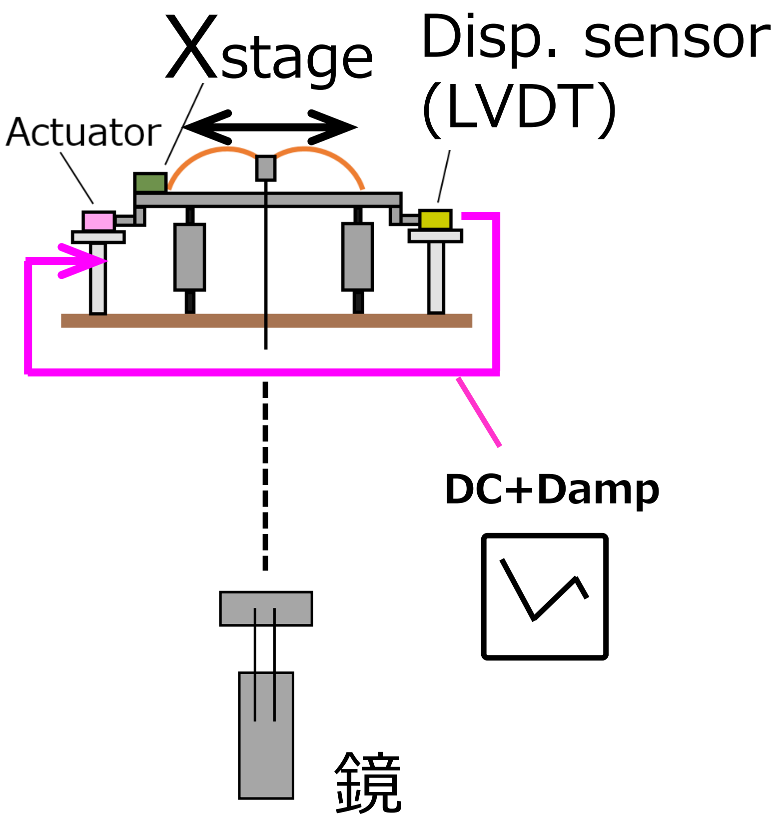


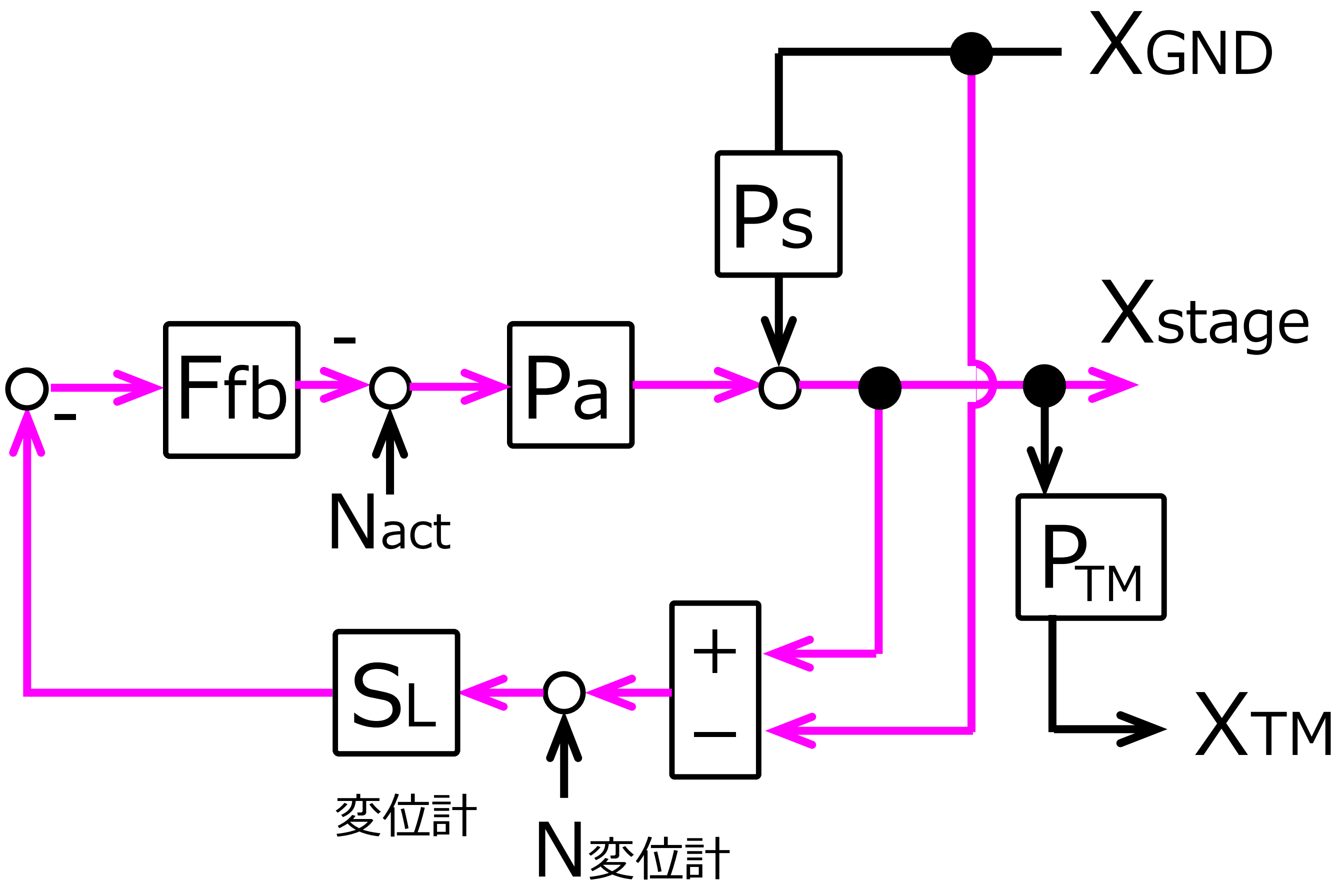
0.2 Hz mode

そのときの鏡の振動 (制御無し)



今回考える制御系 (Lのみ):

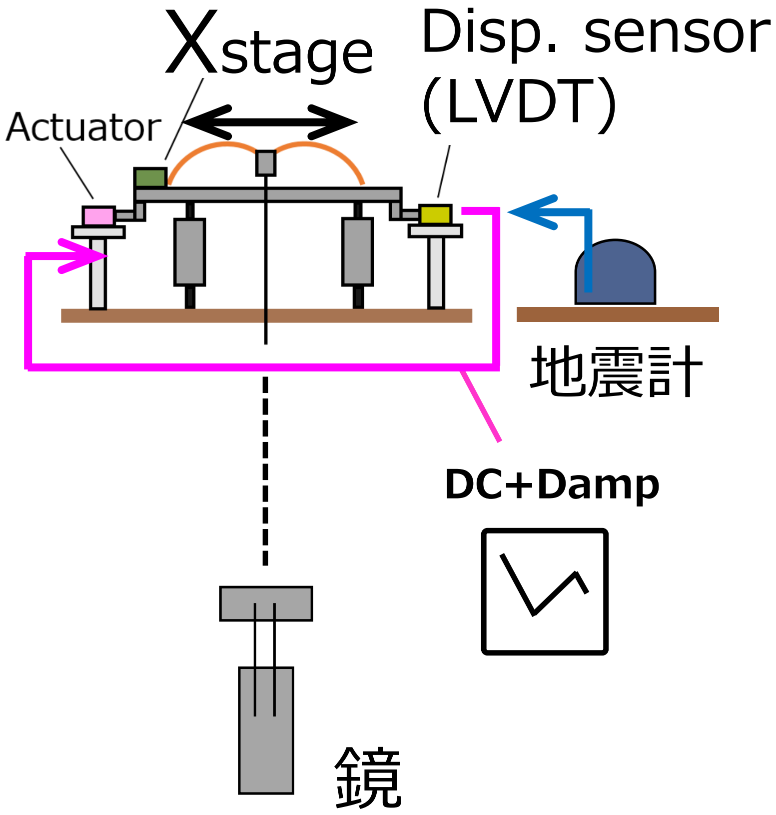


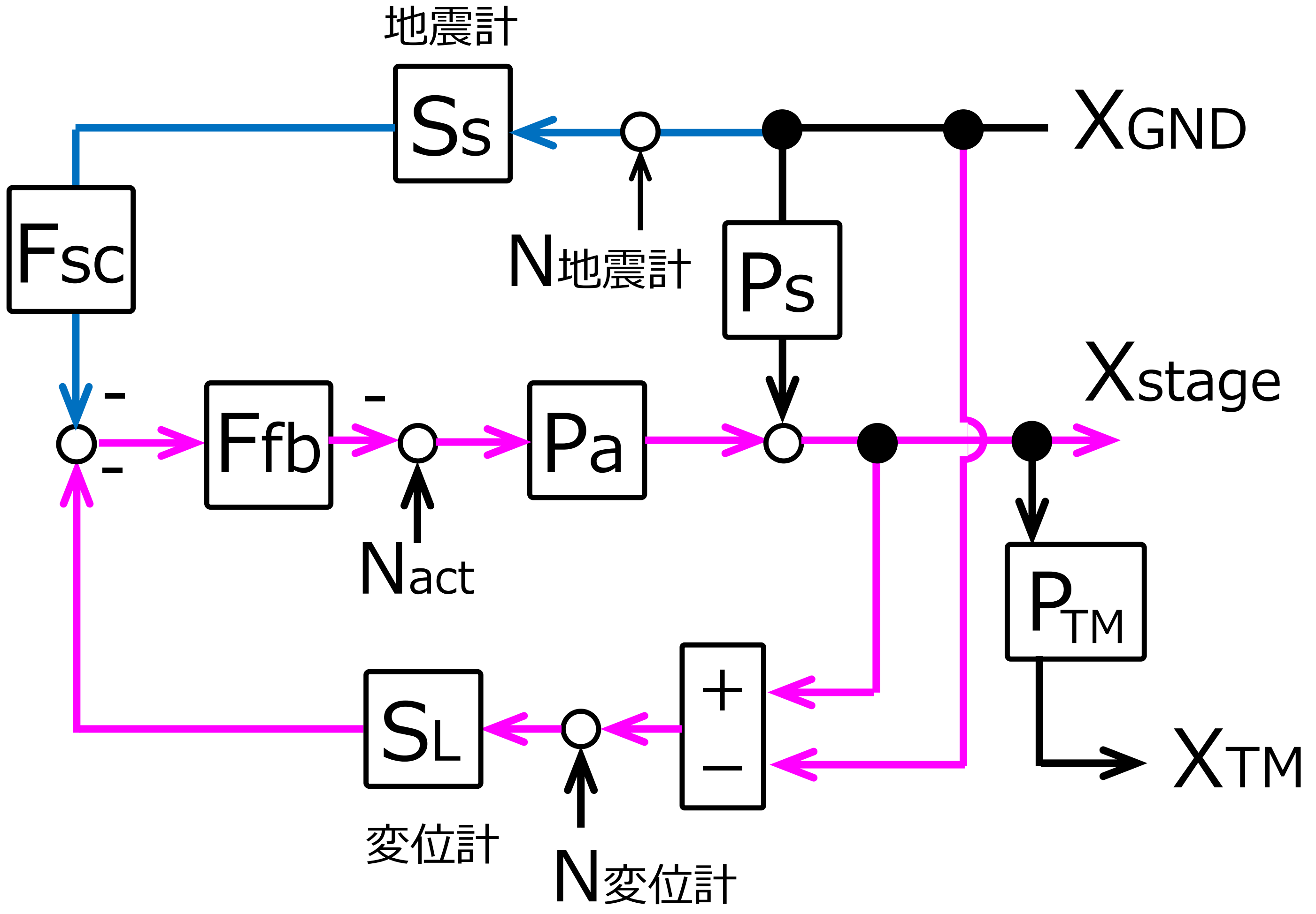


変位計:
$(X_{stage} - X_{GND})$
で制御

→ $X_{stage} \sim X_{GND}$
地面程度は揺れる

今回考える制御系 (Lのみ):

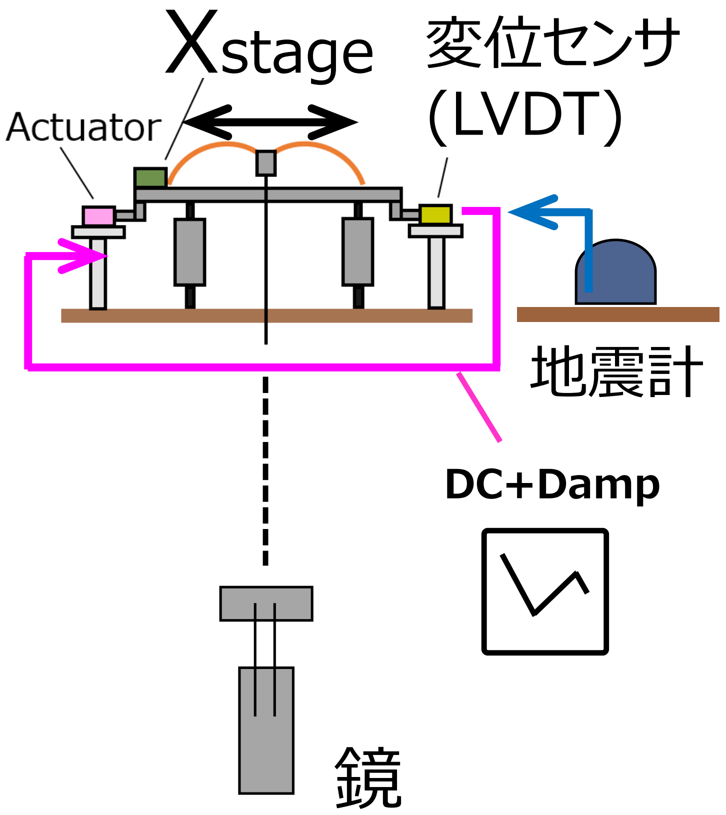


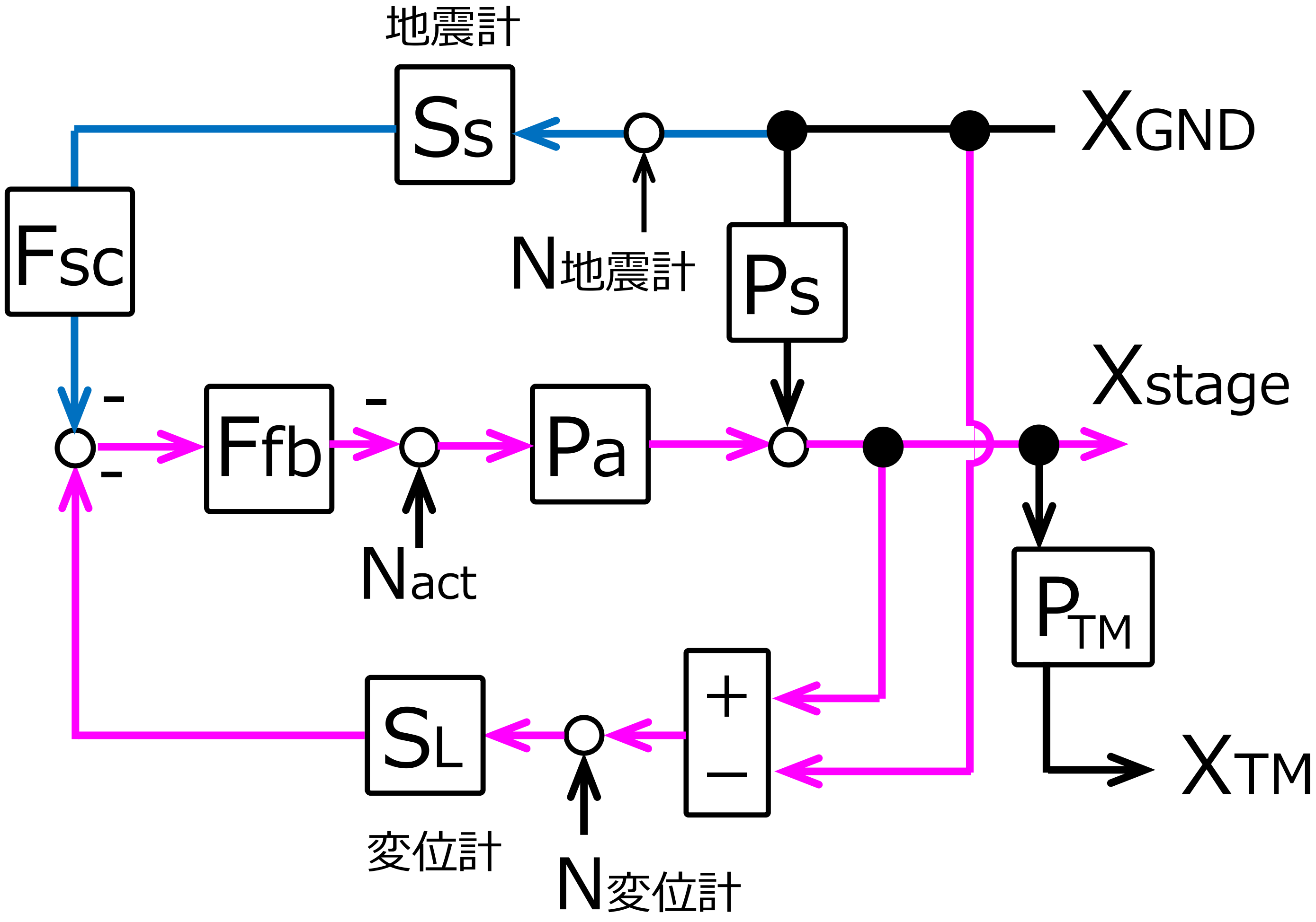


$$X_{stage} = \frac{1}{1+G}\left[G\left(1 - F_{sc}\frac{S_S}{S_L}\right) + P_s\right] X_{GND}$$

$$(\, G = P_a \, F_{fb} \, S_L \,)$$

今回考える制御系 (Lのみ):



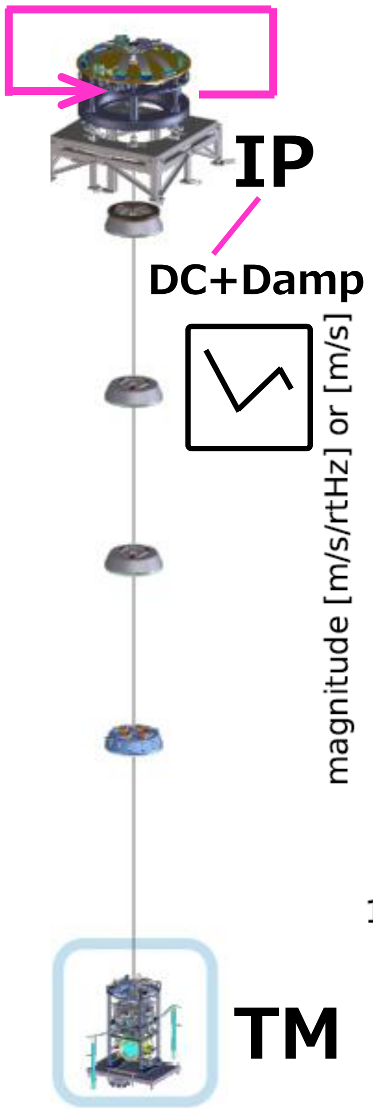


Fsc = SL/Ss にて :

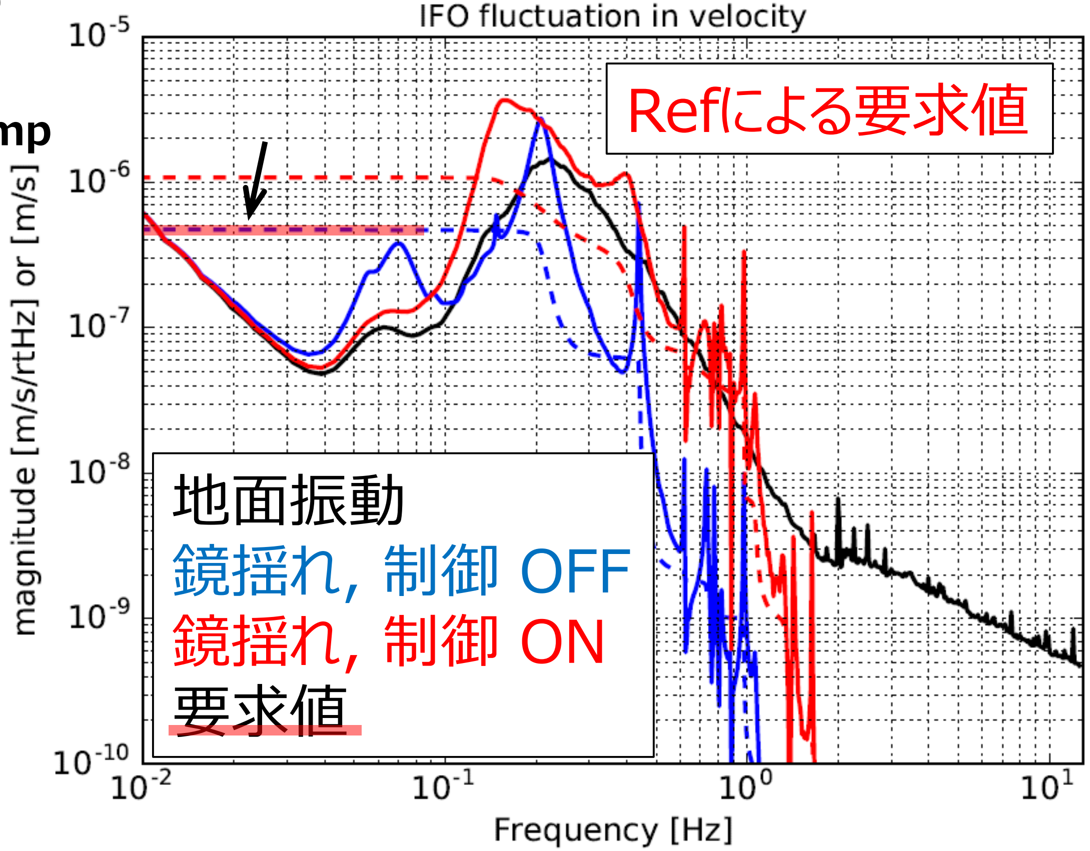
$$X_{stage} = \frac{1}{1+G}\left[G\left(1 - F_{SC}\frac{S_S}{S_L}\right) + P_S\right] X_{GND}$$

Cut the seismic noise injection via LVDT
→ Sensor correction

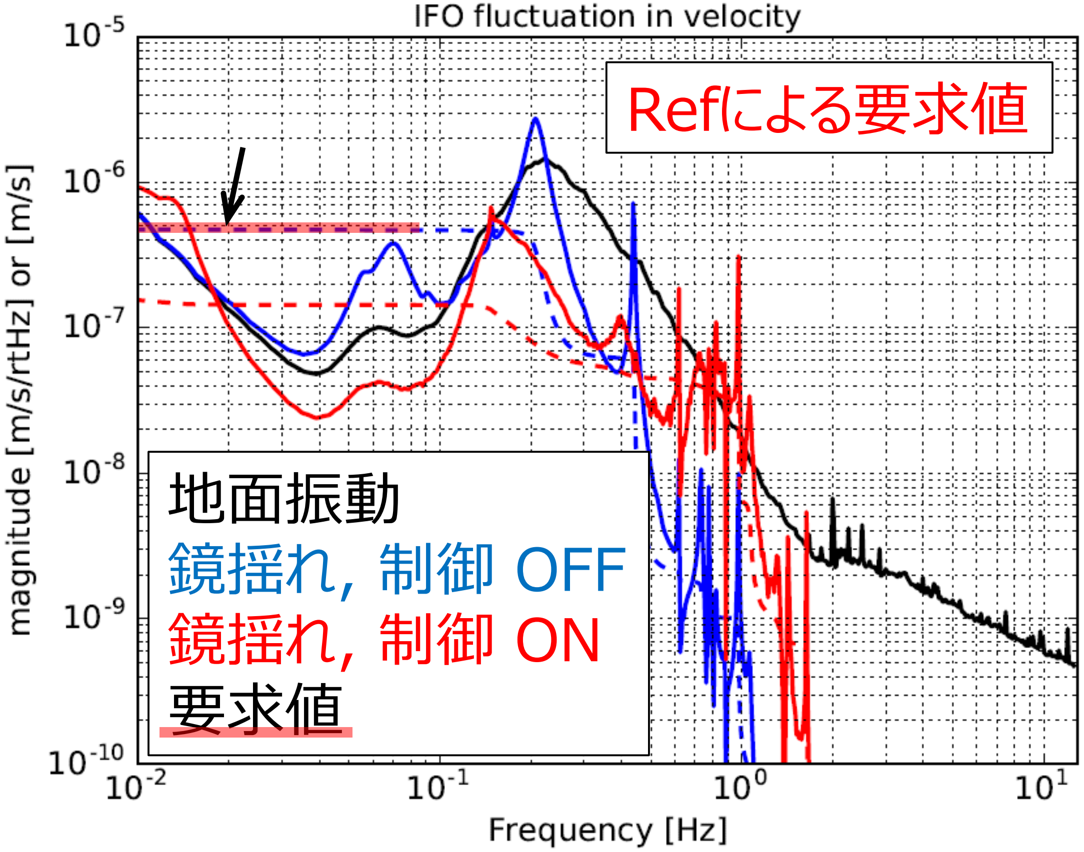
シミュレーション: 90%tile 地面振動を仮定のときの、鏡揺れ(速度)



Sensor correction **OFF**



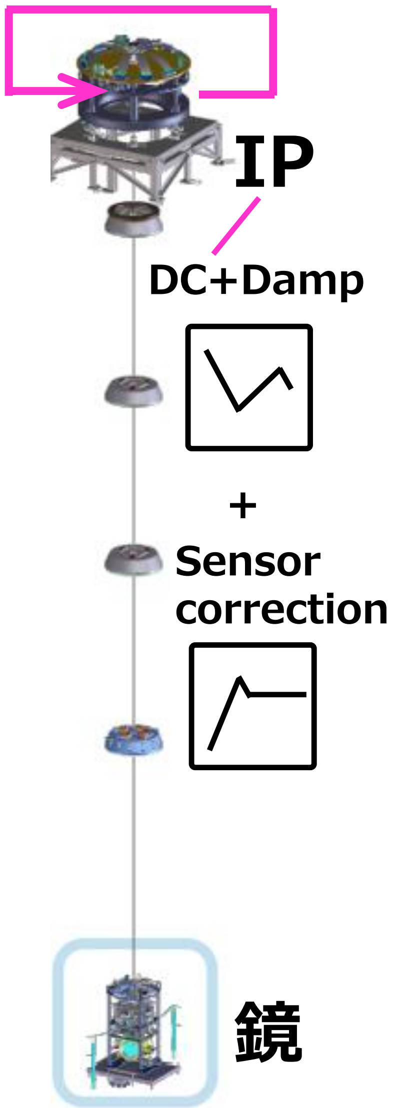
Sensor correction **ON**

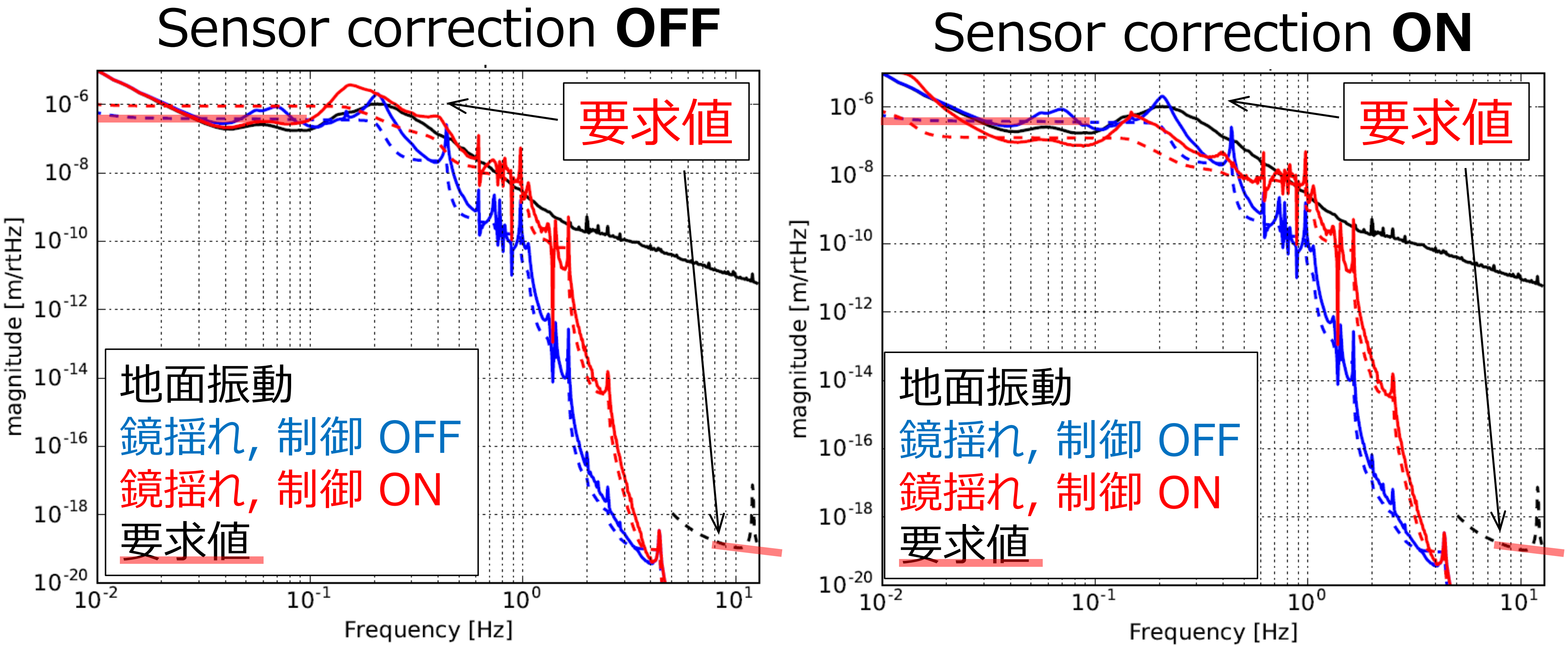


→ Sensor correction を用いて、要求値を満たせる。

Ref: p.55 in https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=6060,
or p.90 in https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/DocDB/ShowDocument?docid=4155

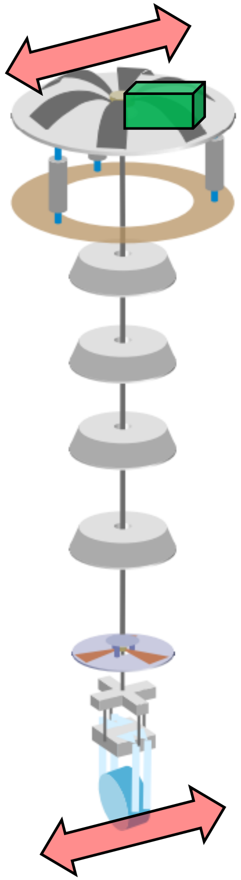
シミュレーション: 90%tile 地面振動を仮定のときの、鏡揺れ

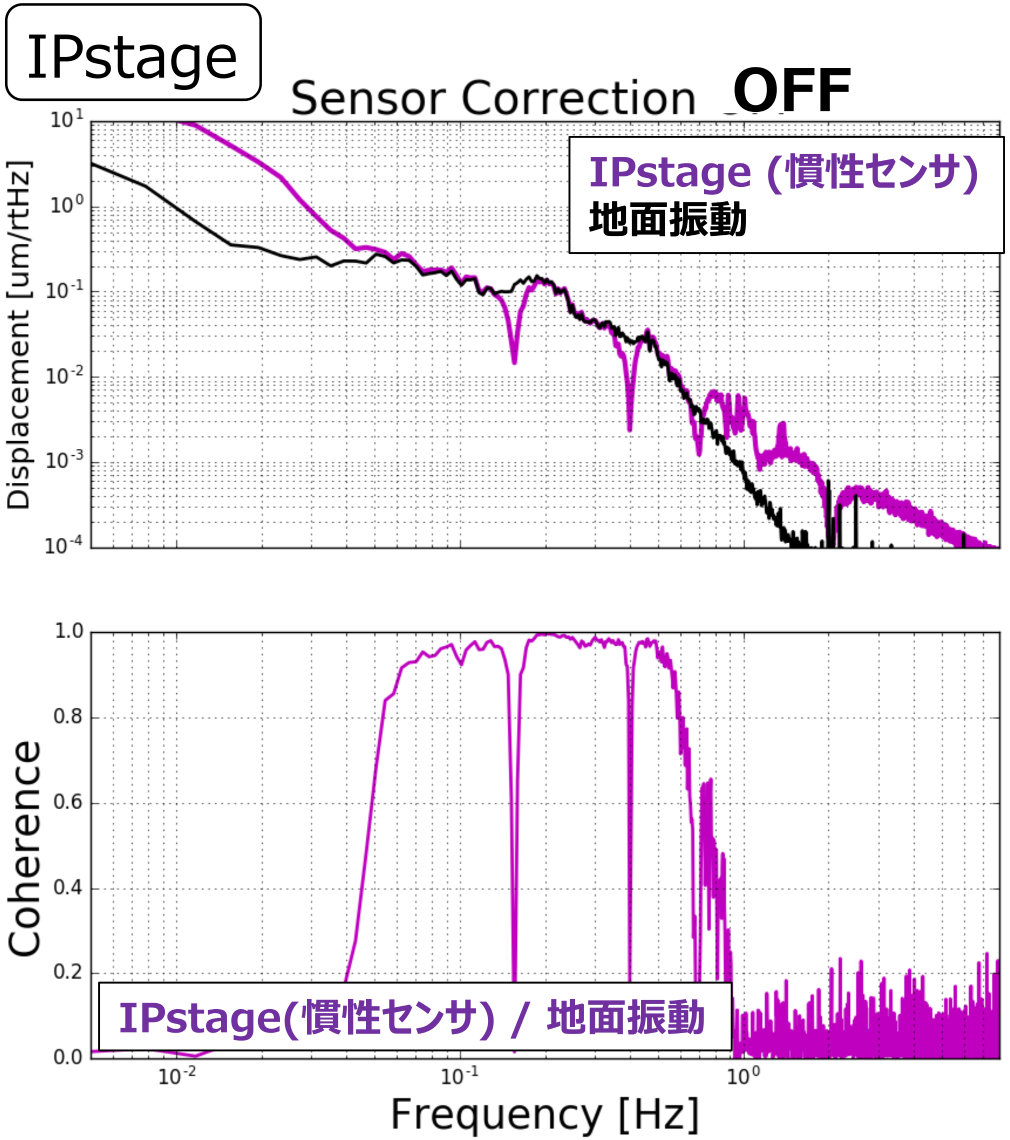


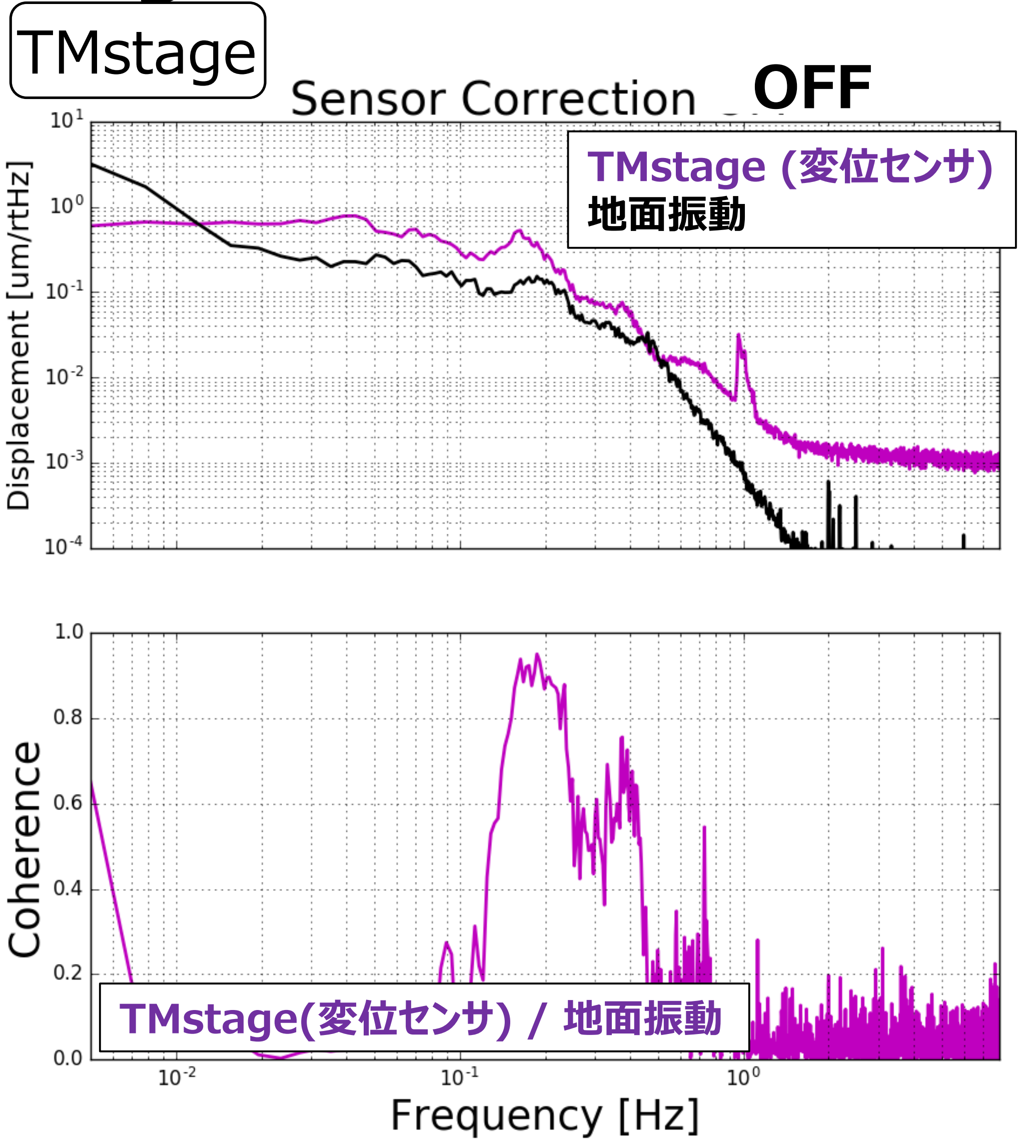


→ Sensor correction を用いて、要求値を満たせる。

テスト実装: 1つのサスペンションのIP-stageに実装







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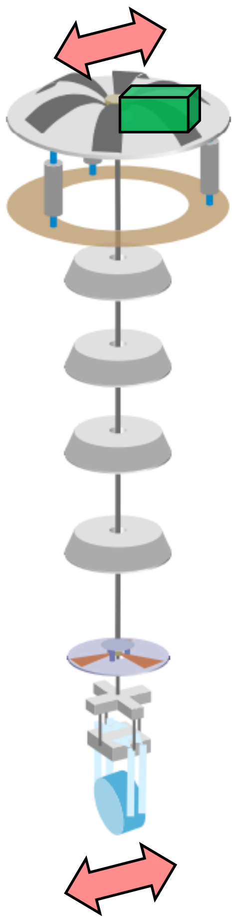
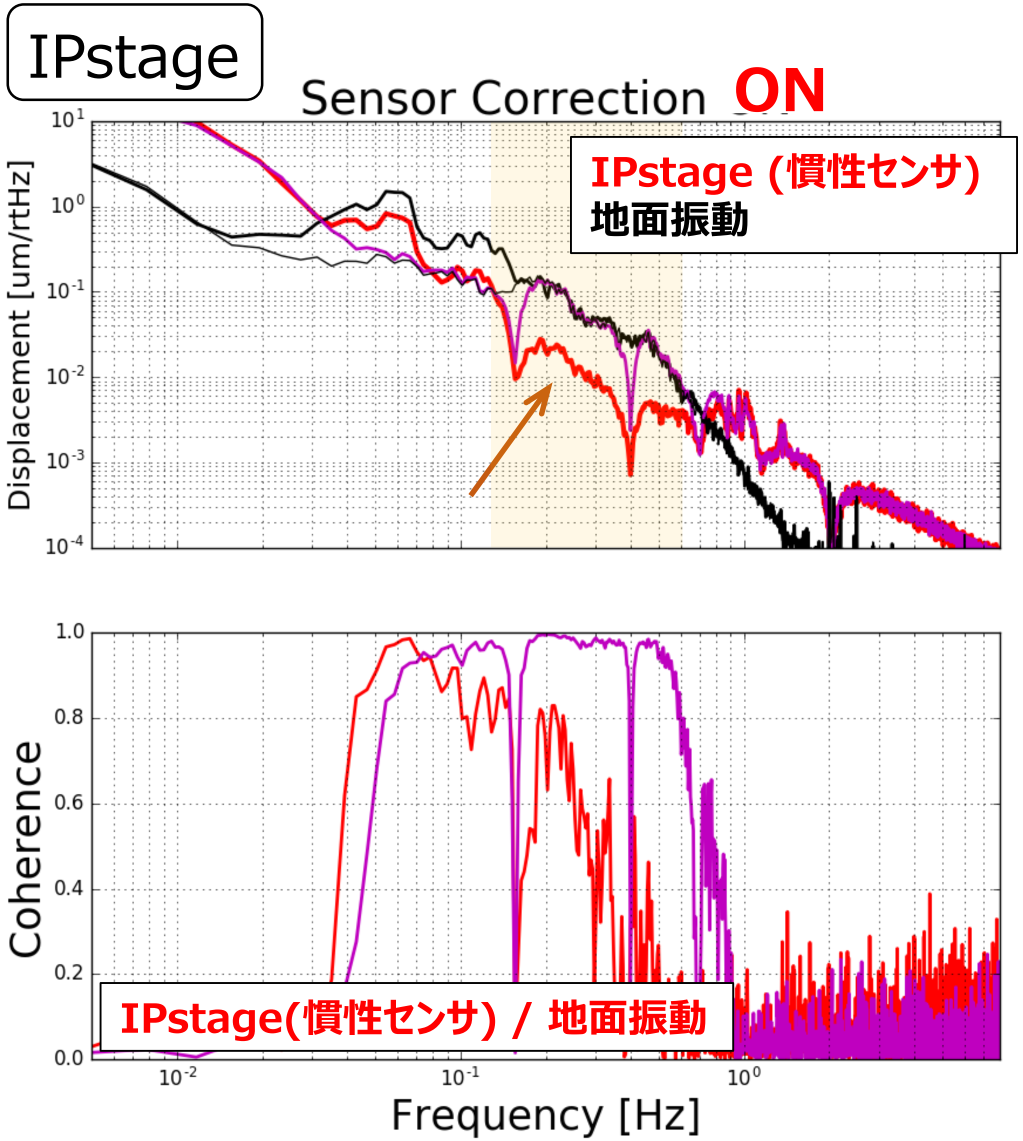
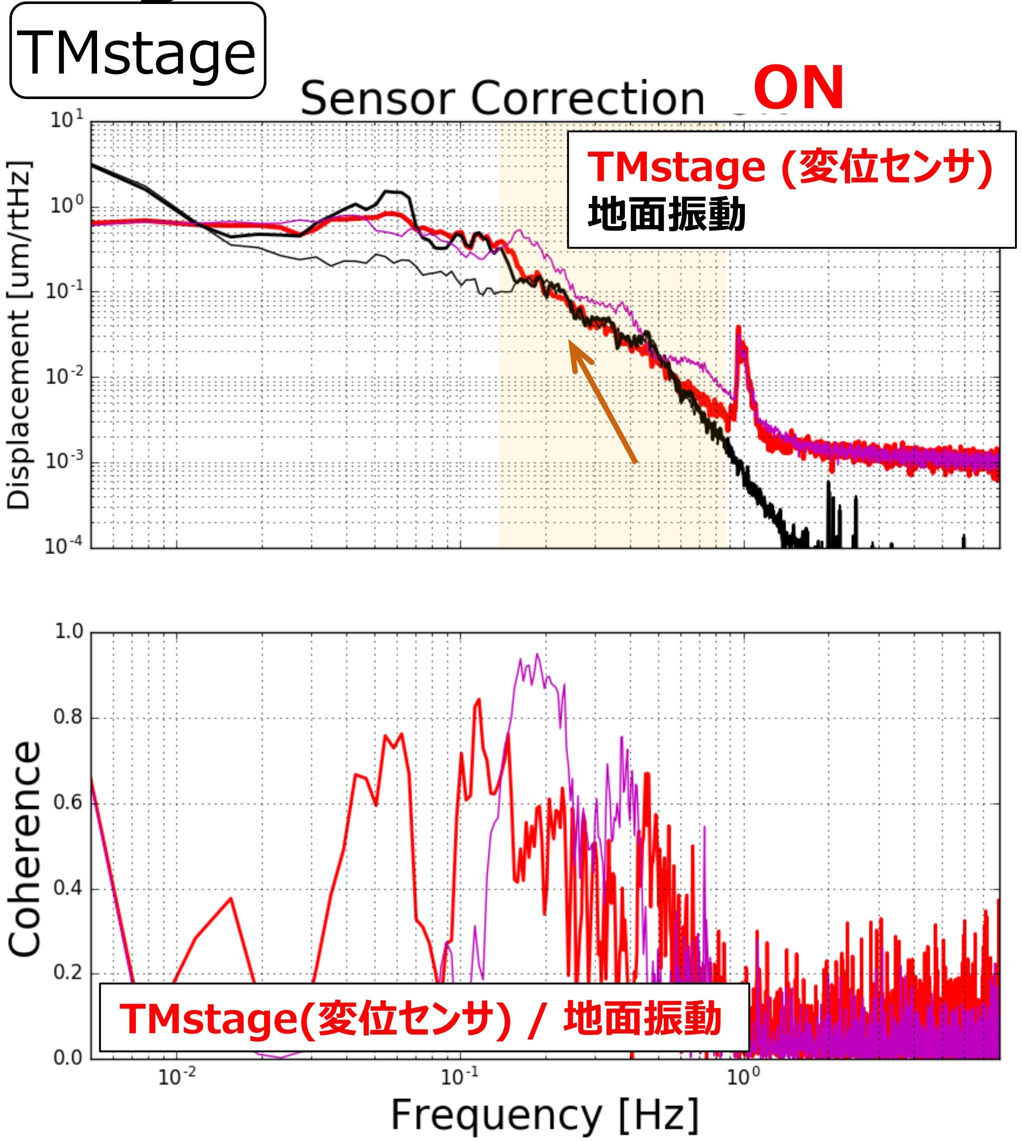
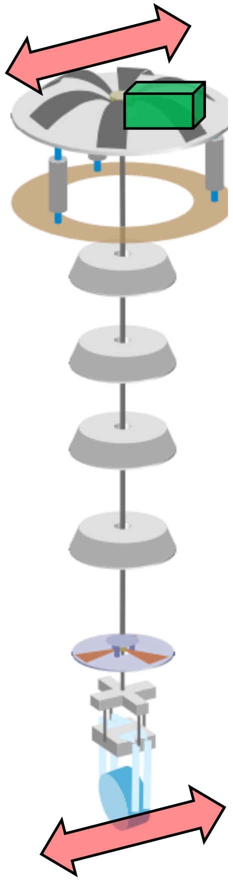




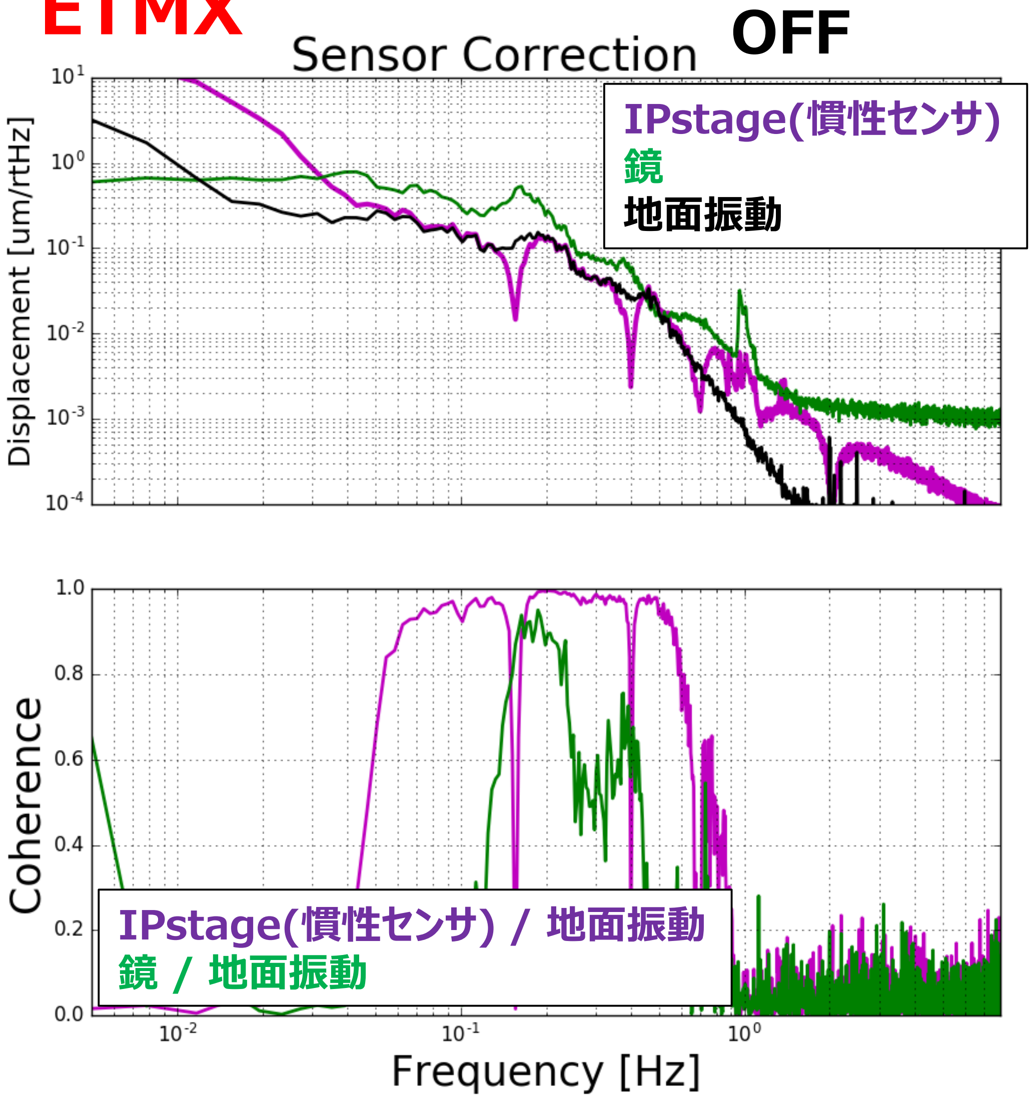


→ SC worked at 0.15 ~ 0.7Hz (only).

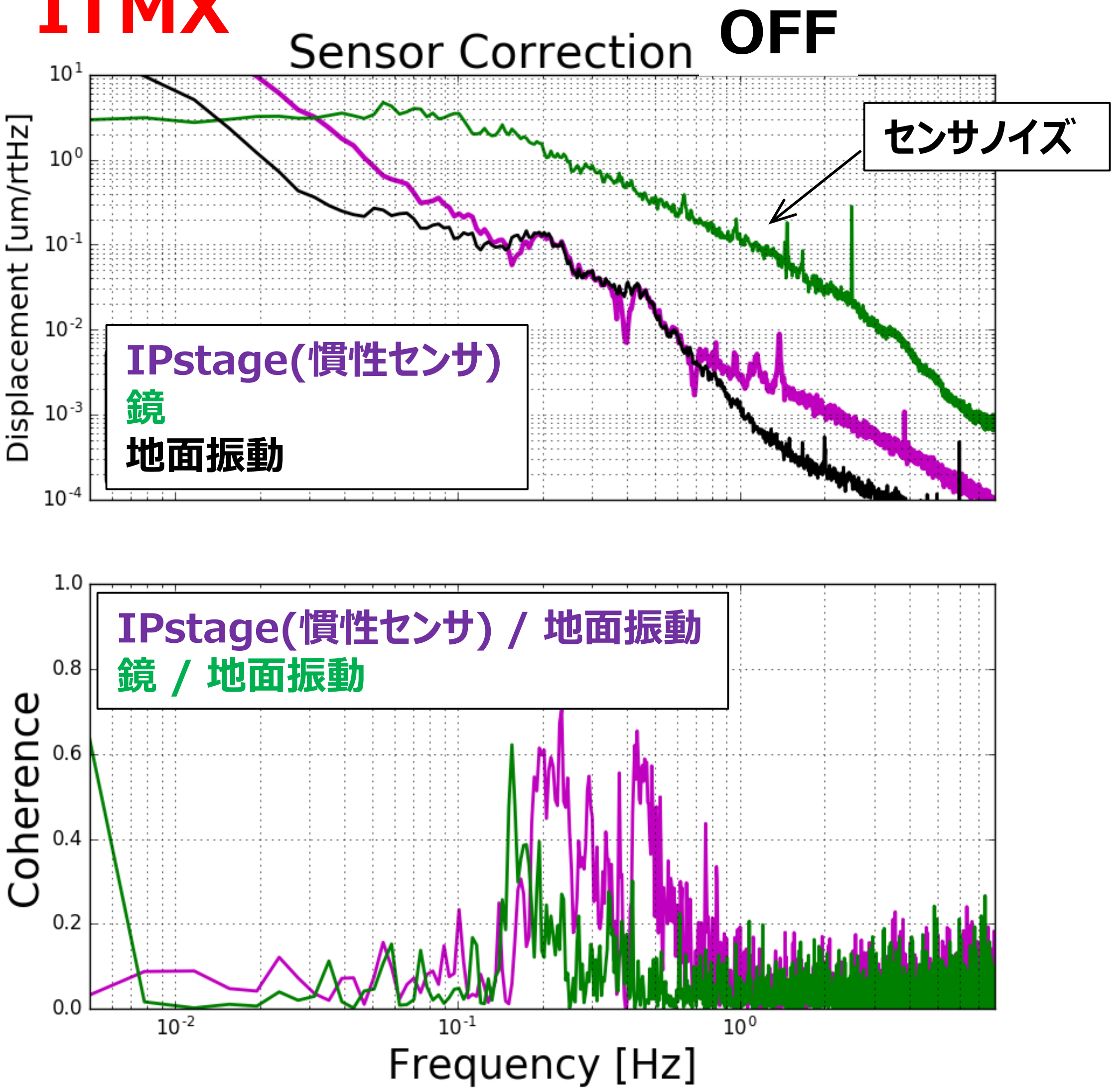
テスト実装: 2つのサスペンションのIP-stageに実装、local で見ると



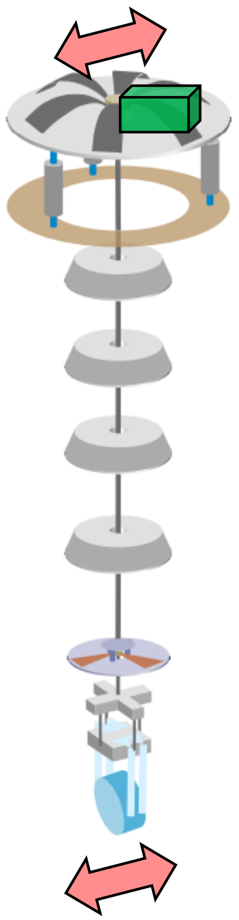
ETMX

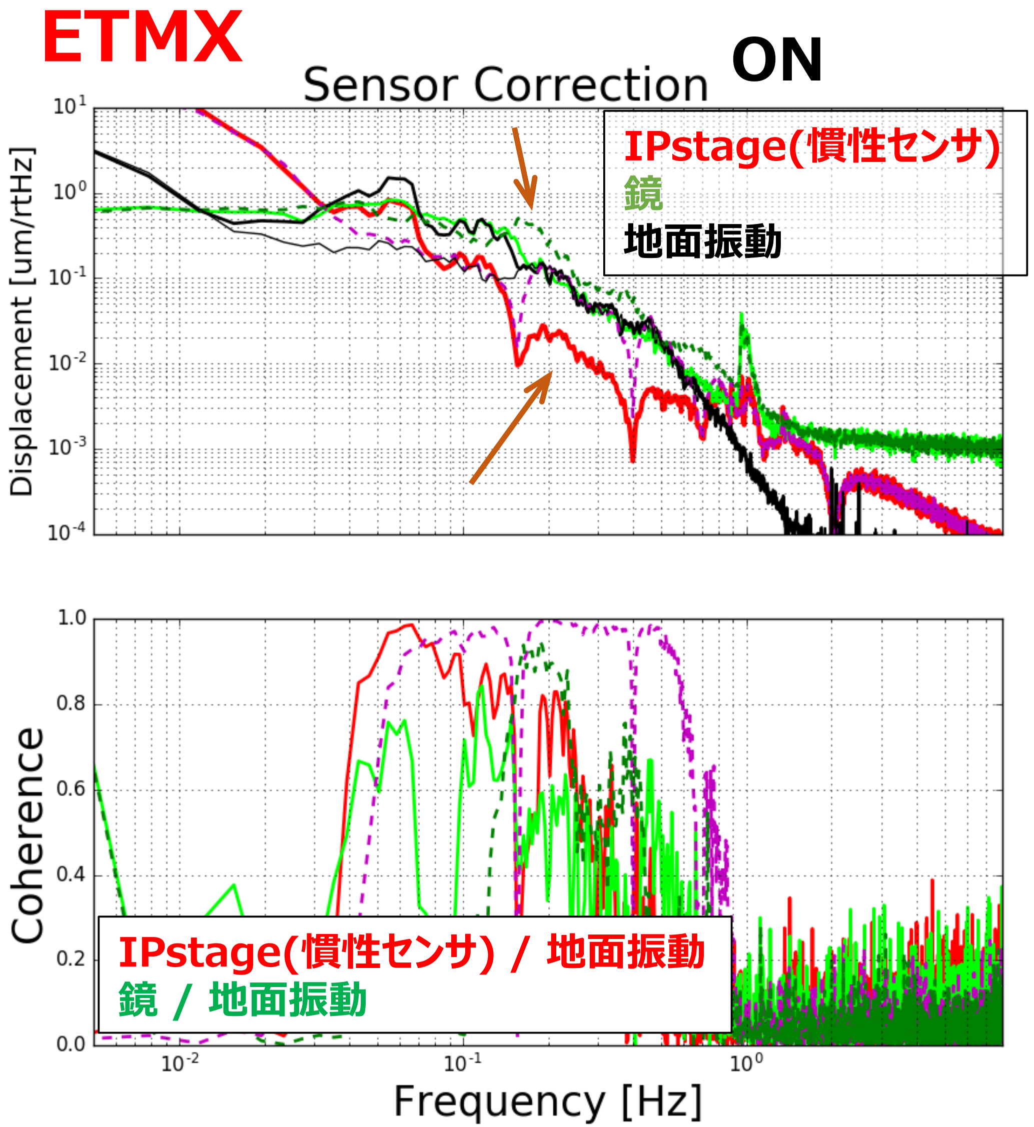


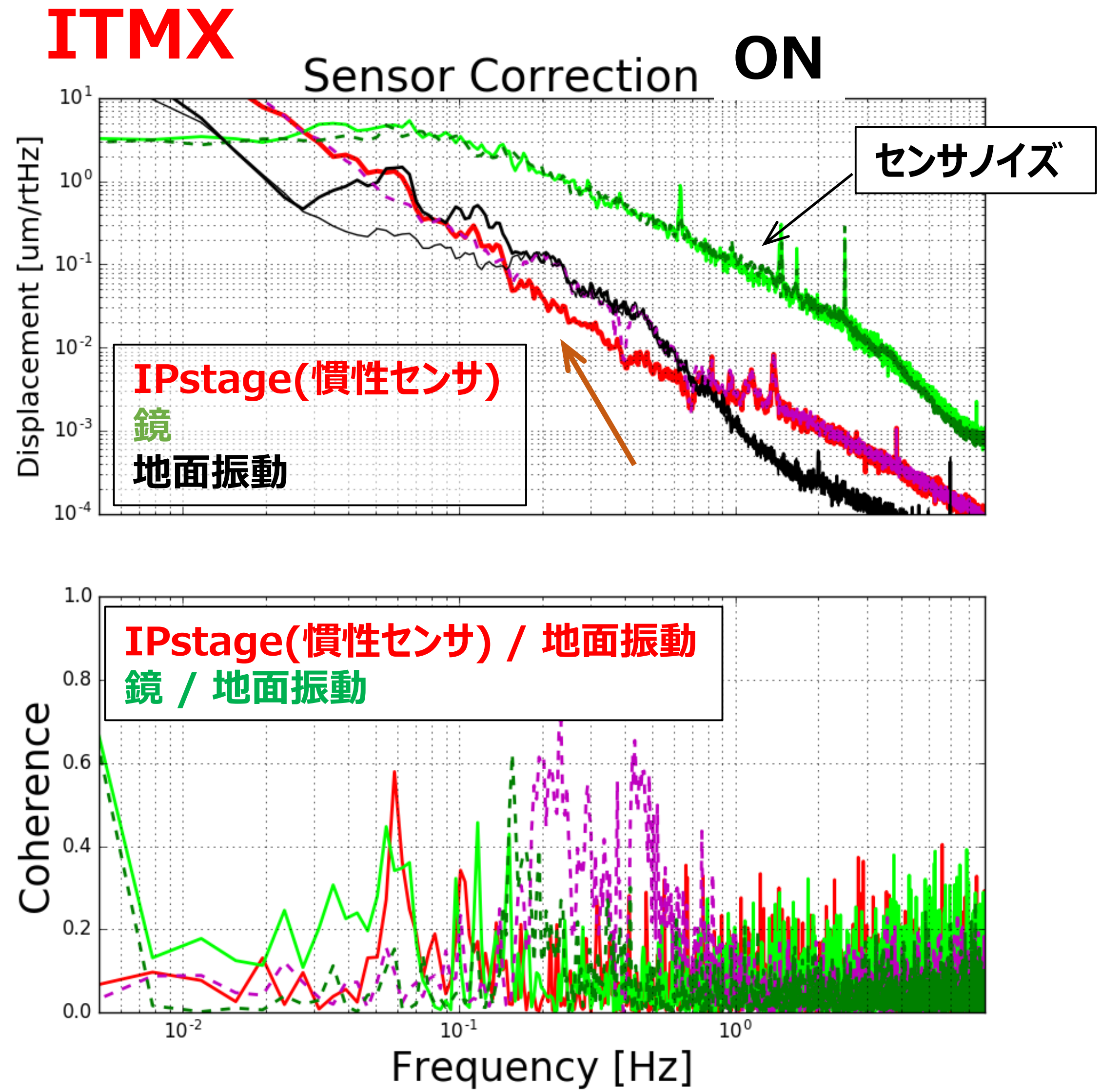
ITMX



テスト実装: 2つのサスペンションのIP-stageに実装、local で見ると

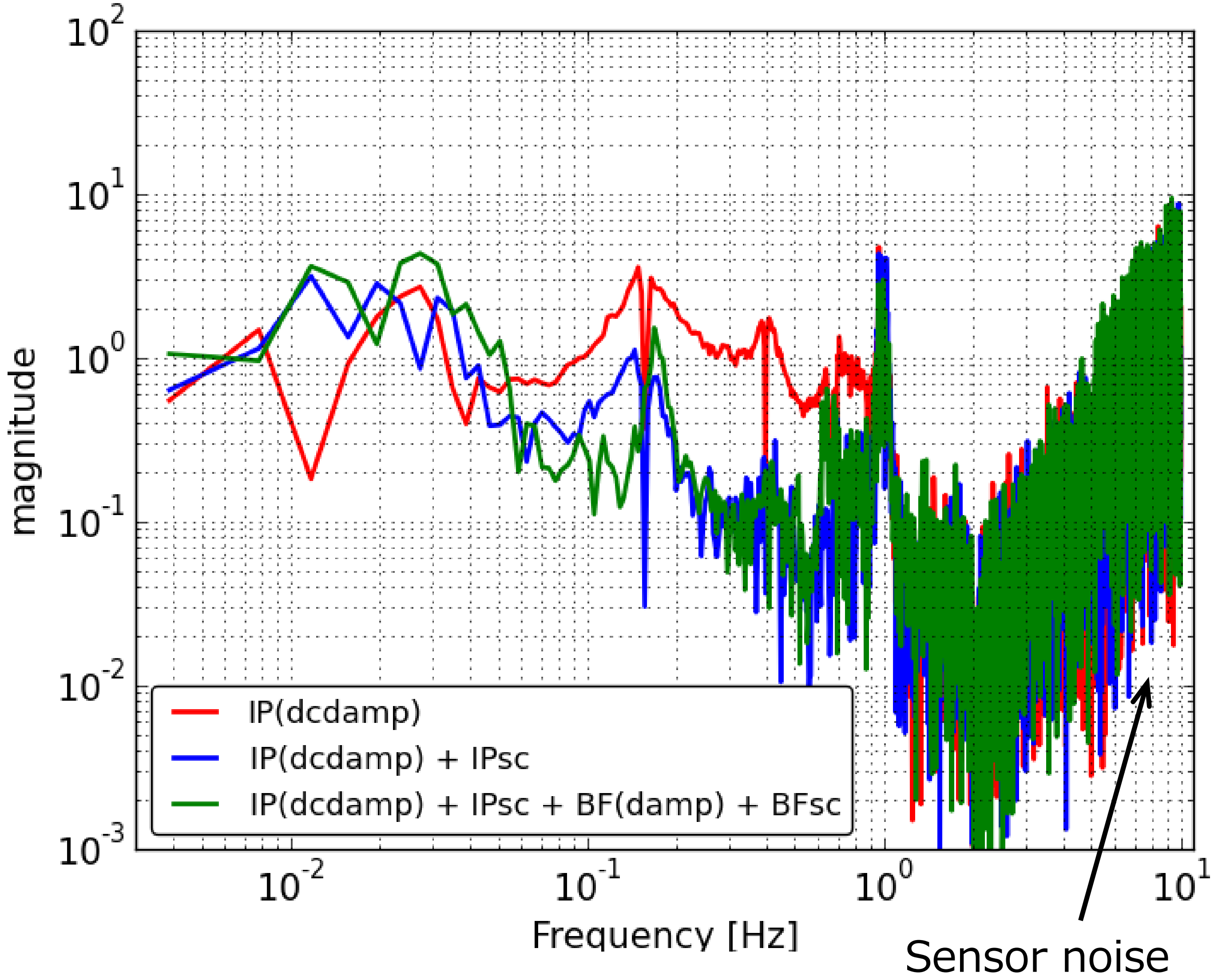






→ 0.12 – 0.7Hz で揺れが低減された様子。詳細はセンサノイズ/地面振動に隠れた。

By combining (TML/IPL)*(IPL/GNDL)



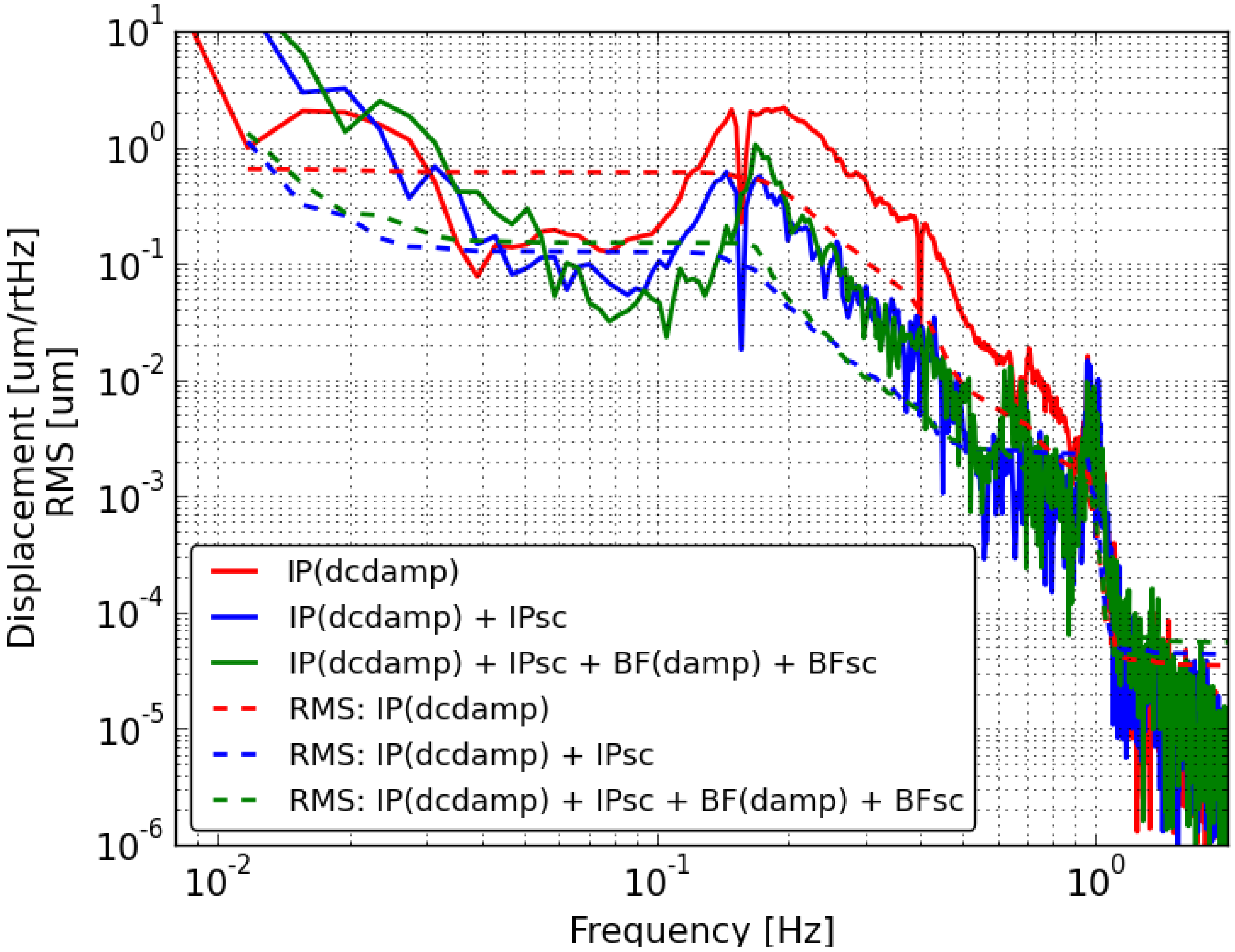
Displacement TF:
From GND to TML

(measured at ETMX)

Is notch real?
→ Not sure.
→ tilt coupling from Geophone
Or
→ Actual mechanical response

Whichever, the conclusion is same.

By combining (TML/IPL)*(IPL/GNDL)*(GNDL_model)

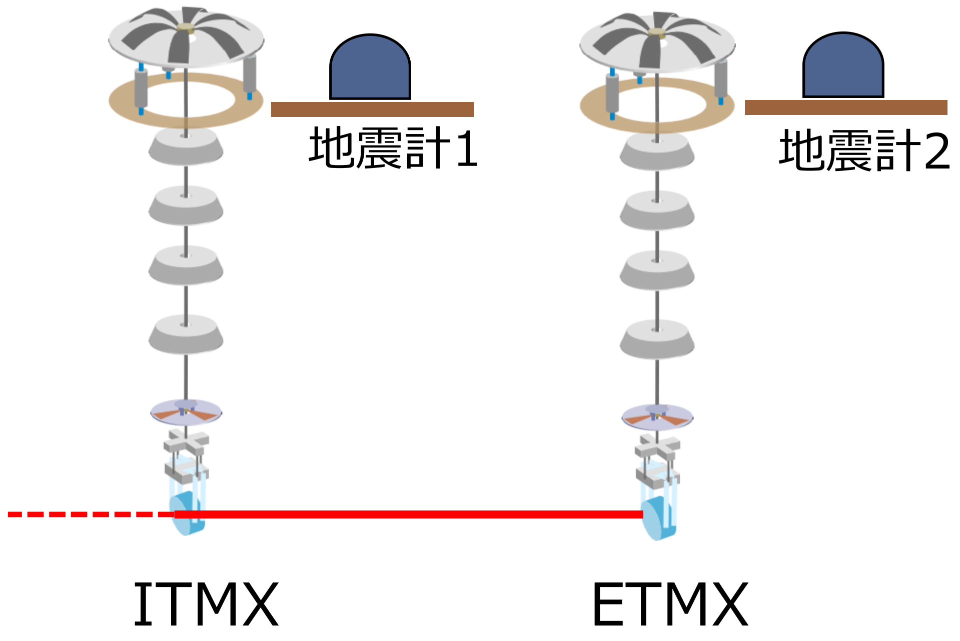


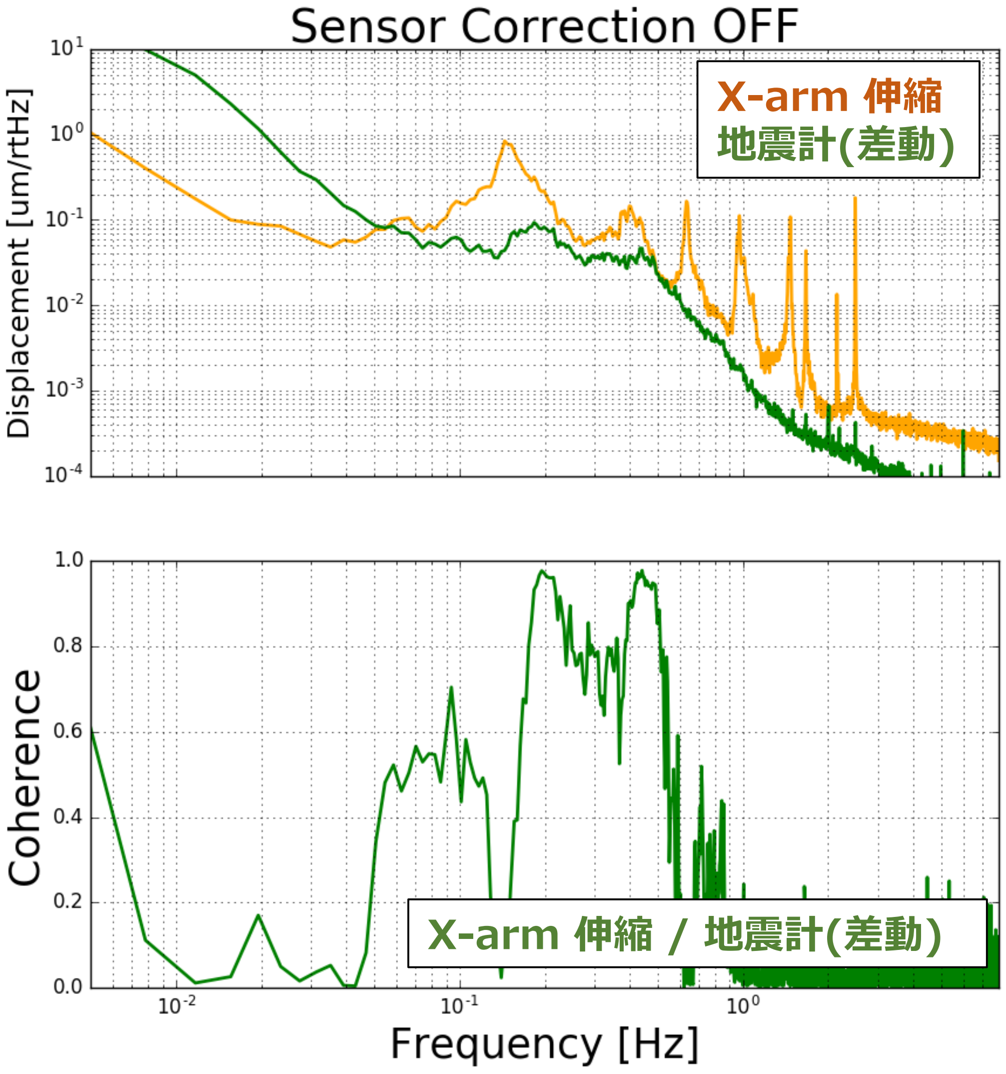
Disp. TF:

From GND to TML

テスト実装: 2つのサスペンションのIP-stageに実装、Xarm で見ると

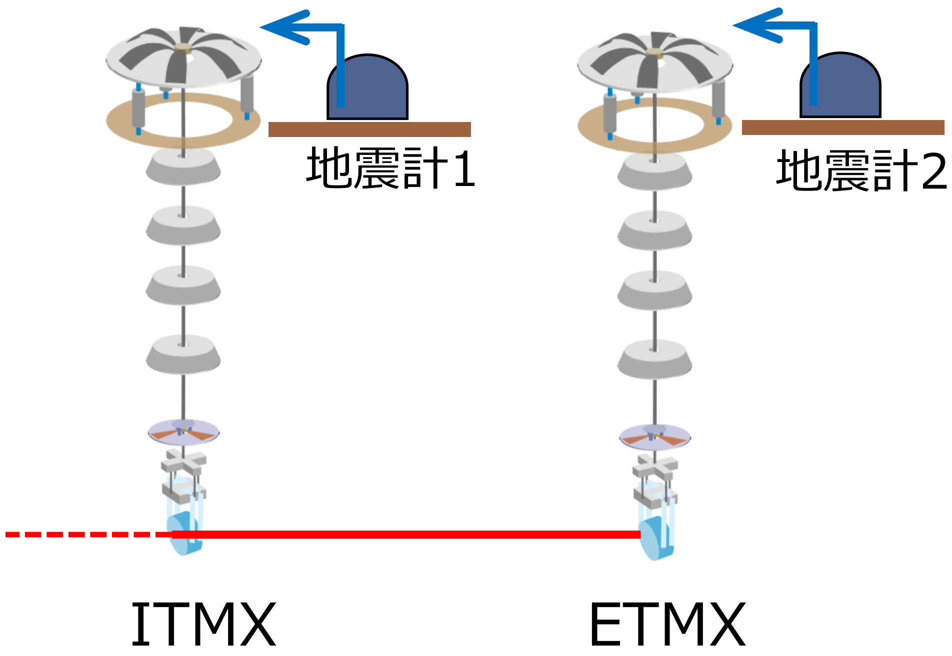
- → ETMX と ITMX に実装
  - → 0.15 ~ 0.7 Hzにて同様な改善あり
- → X-arm (FP cavity) の共振器長の確認

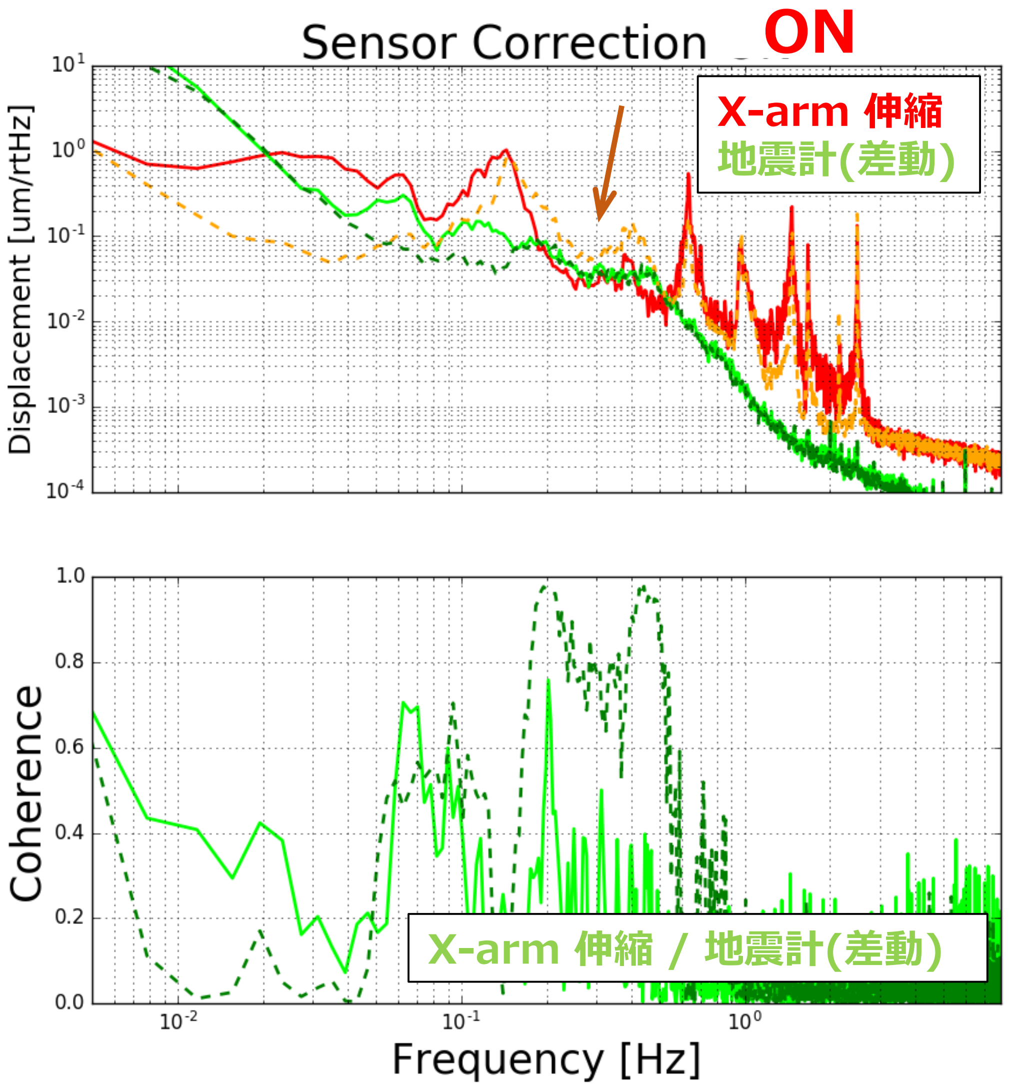




テスト実装: 2つのサスペンションのIP-stageに実装、Xarm で見ると

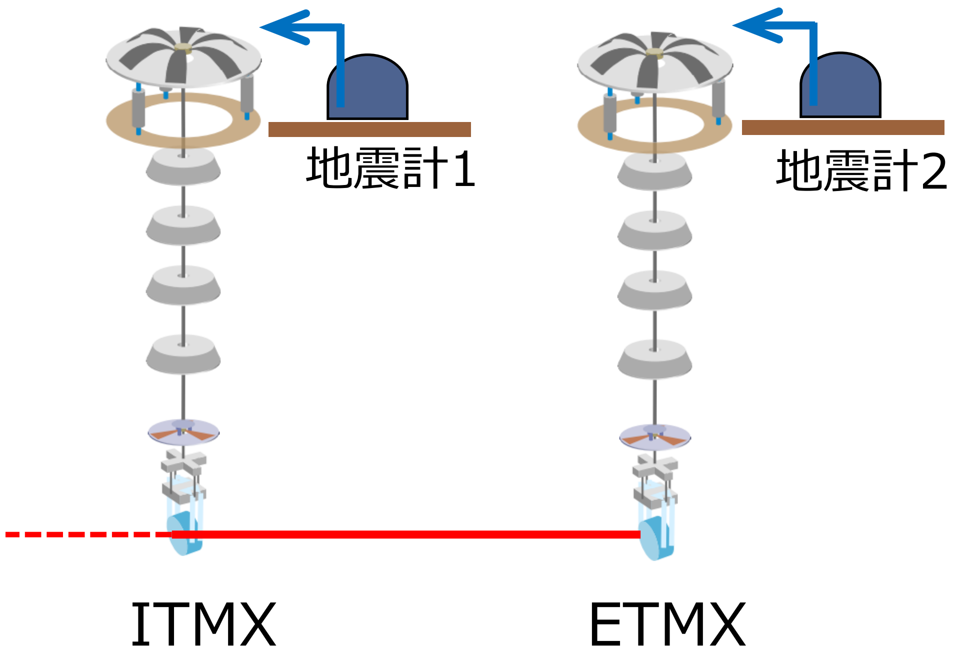
→ X-arm (FP cavity) の共振器長では

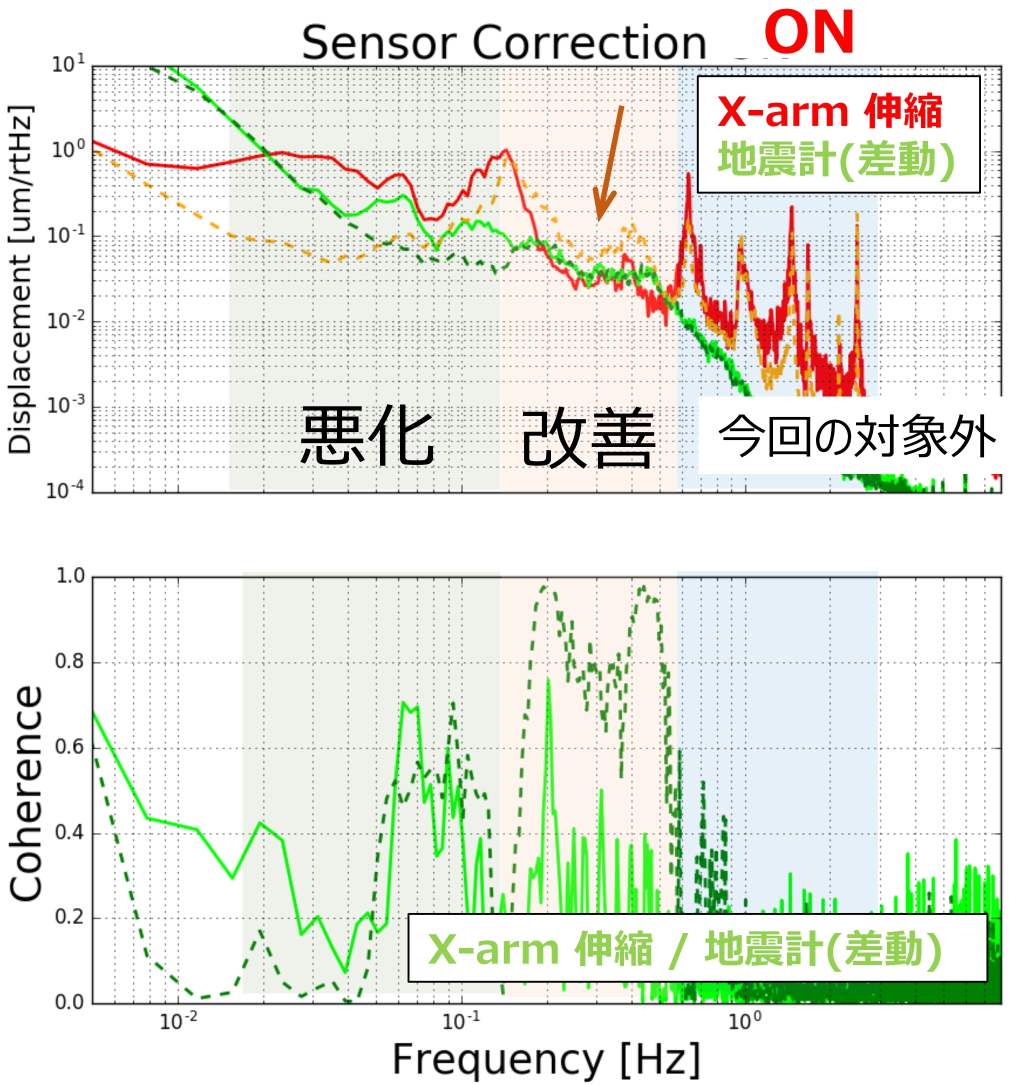




テスト実装: 2つのサスペンションのIP-stageに実装、Xarm で見ると

→ X-arm (FP cavity) の共振器長では



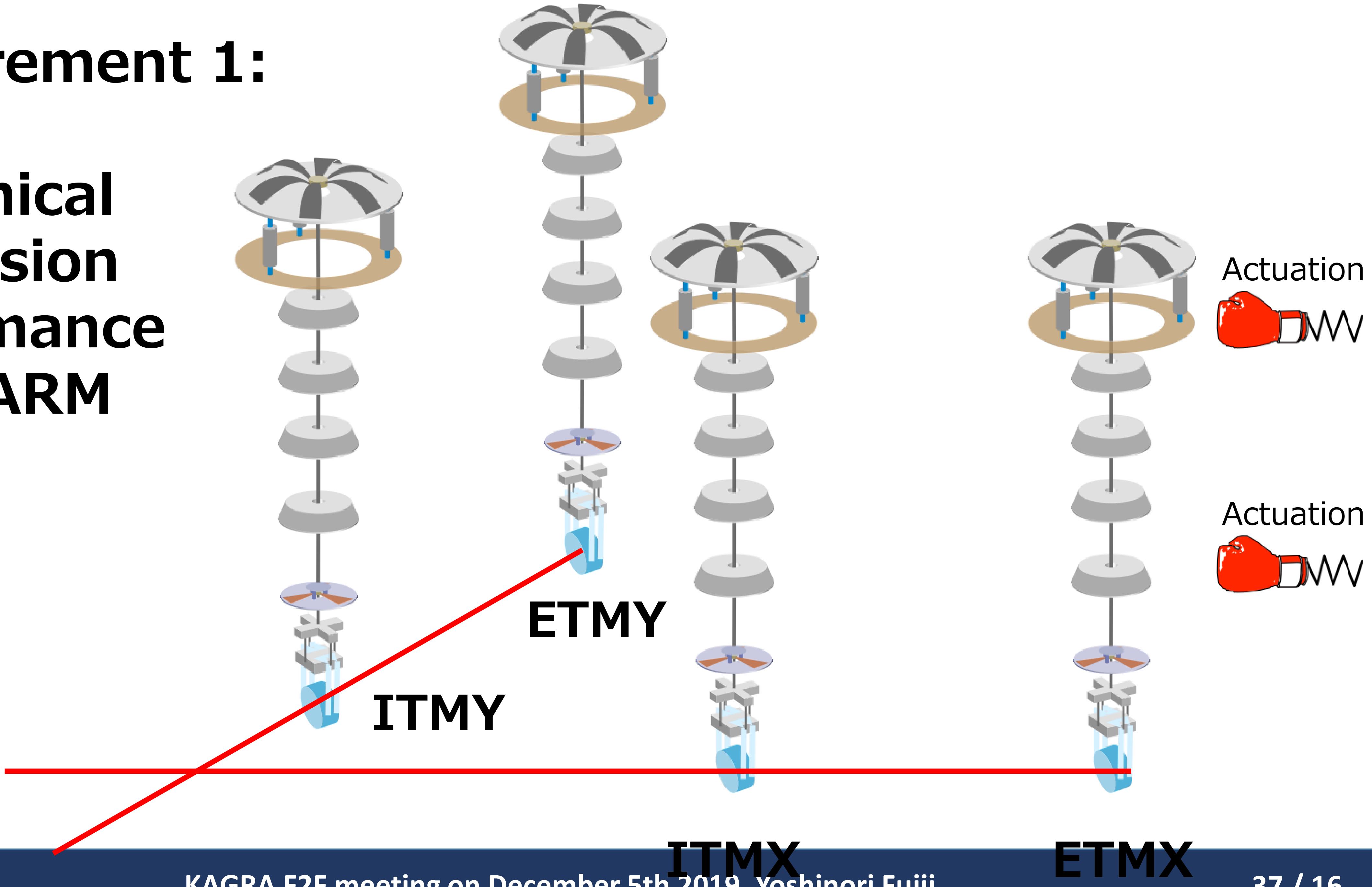


-- SC worked at 0.15 ~ 0.6Hz.
-- 低周波: 悪化
→ SC filterからの地震計の雑音の流入ほか
→ To be investigated.

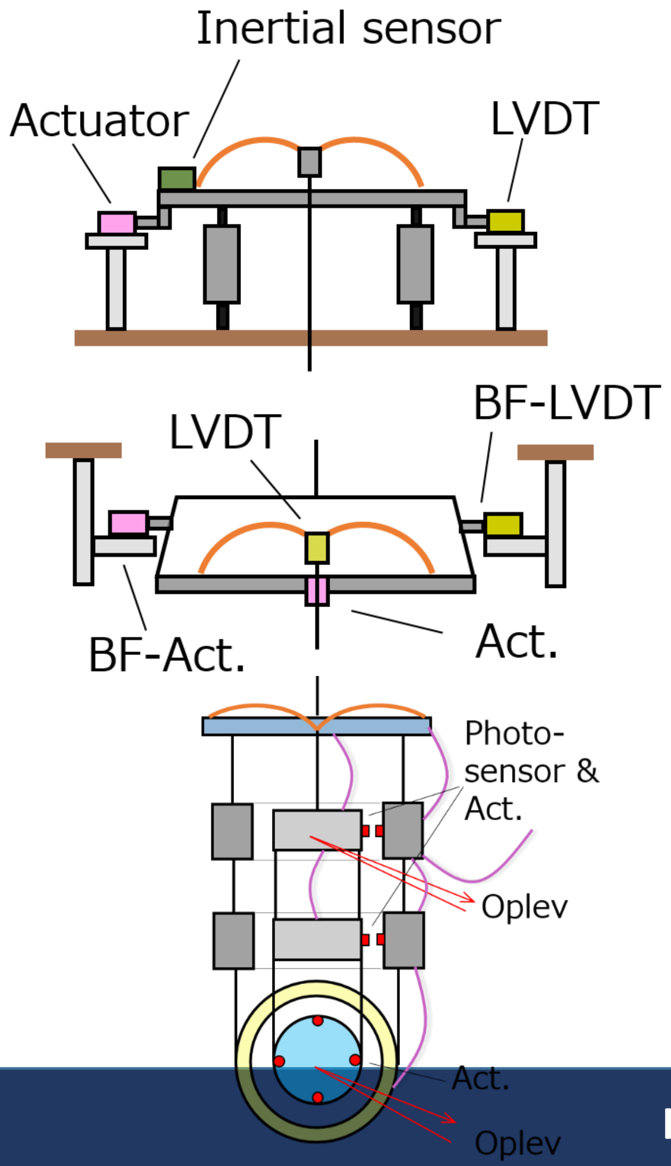
Verification of suspension performance

Measurement 1:

Mechanical suspension performance with DARM

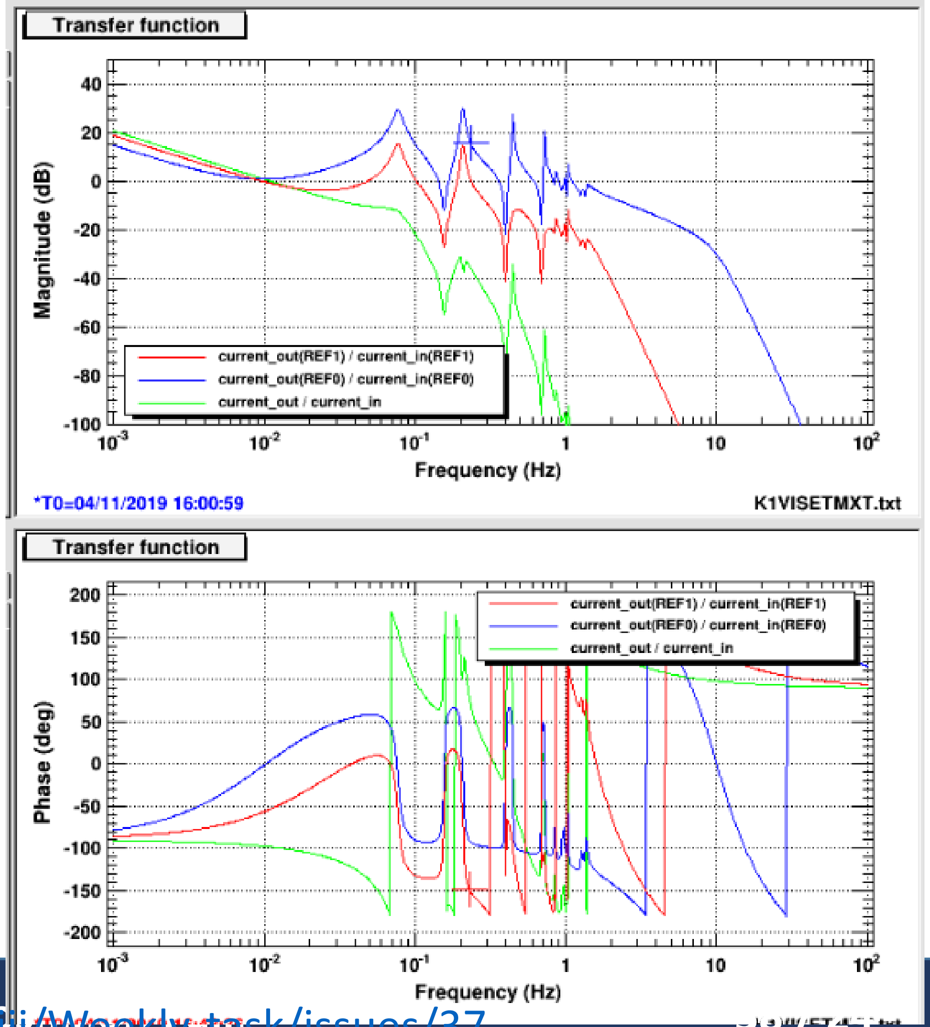


Settings for the measurement w/o controls:



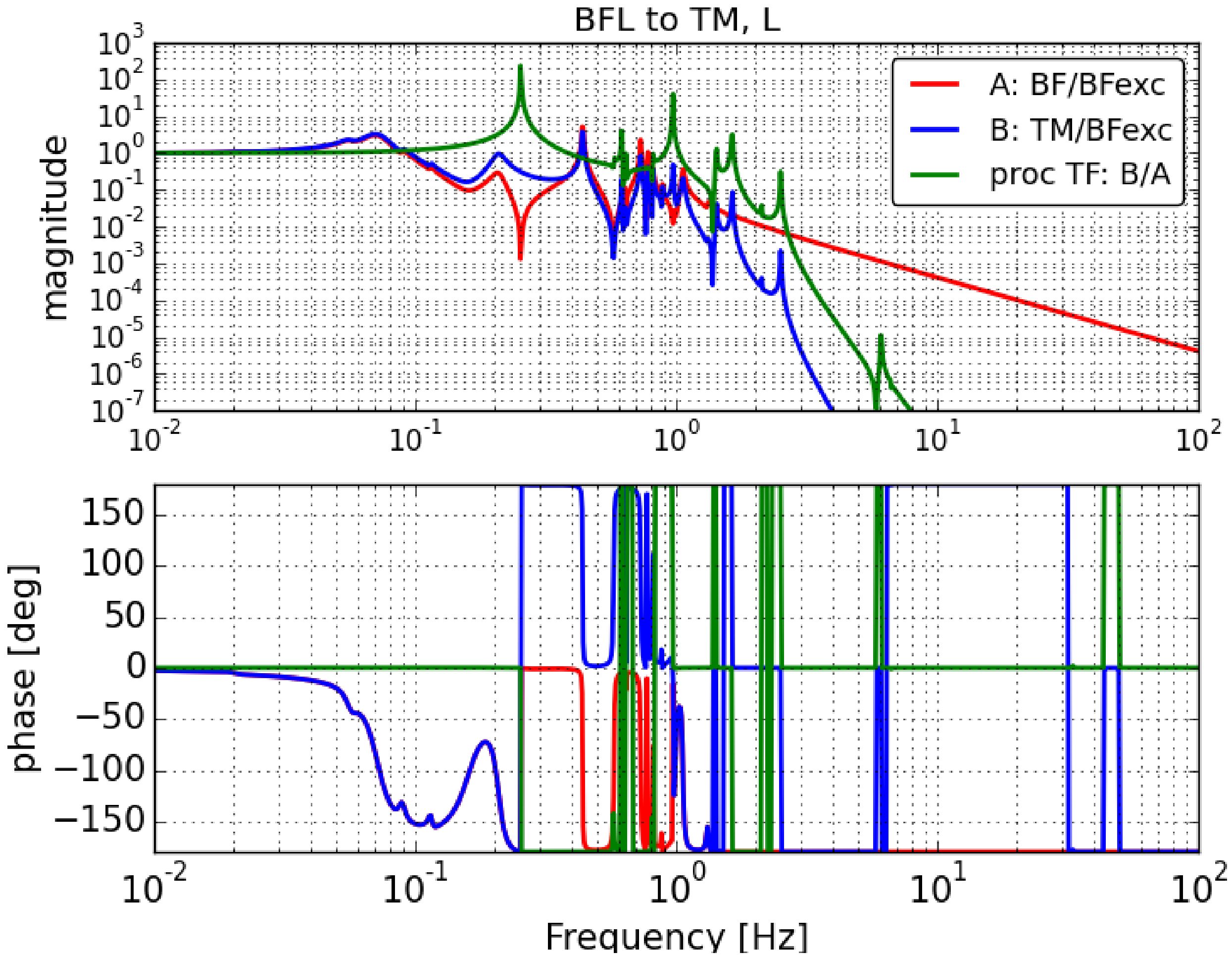
With Tower-damped state,

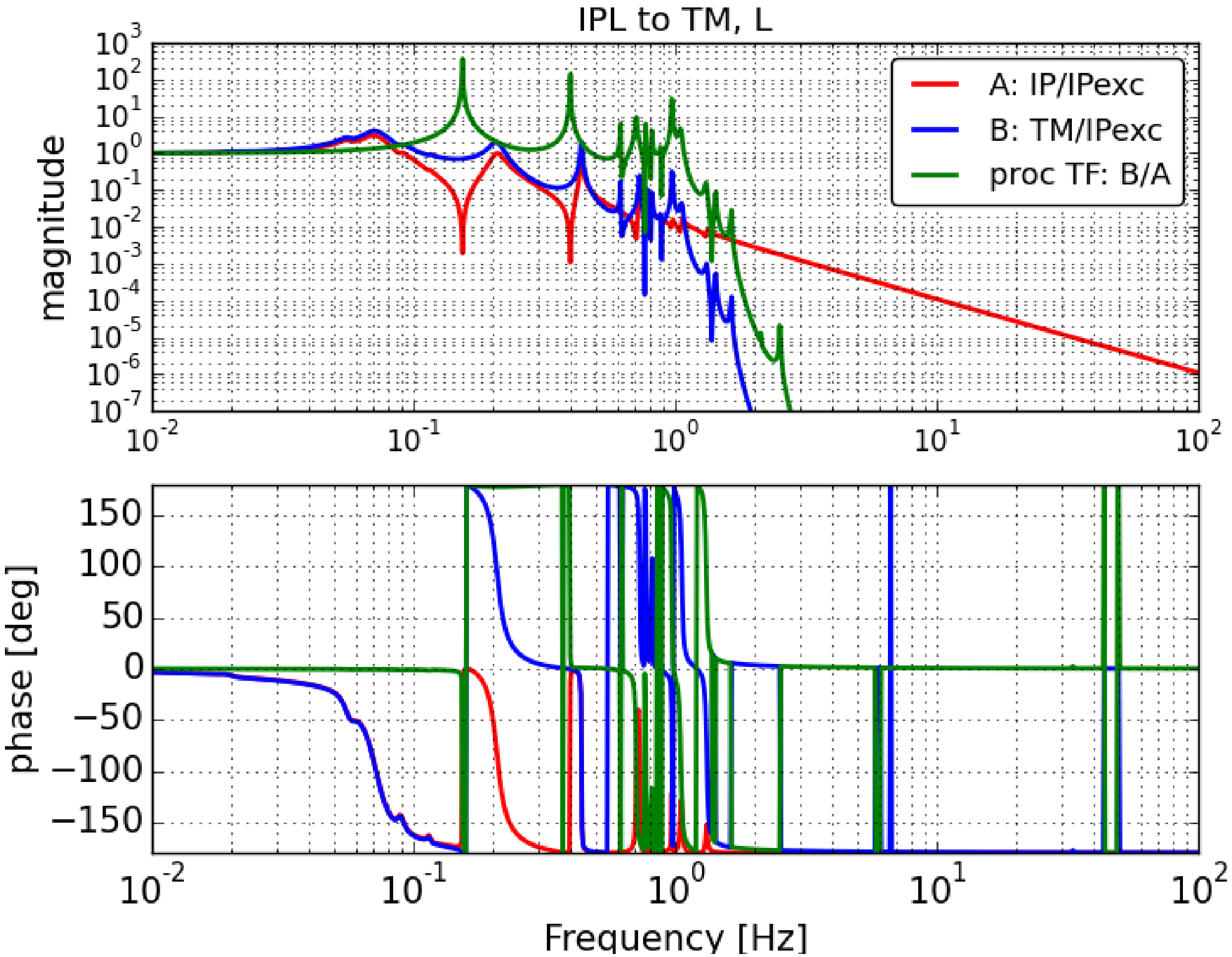
- ordinal L-loop (blue) was opened at IP satge.
- instead,
  - green curve loop was used for the ALS_DARM measurement,
  - red curve loop was used for the FPMI_DARM measurement.



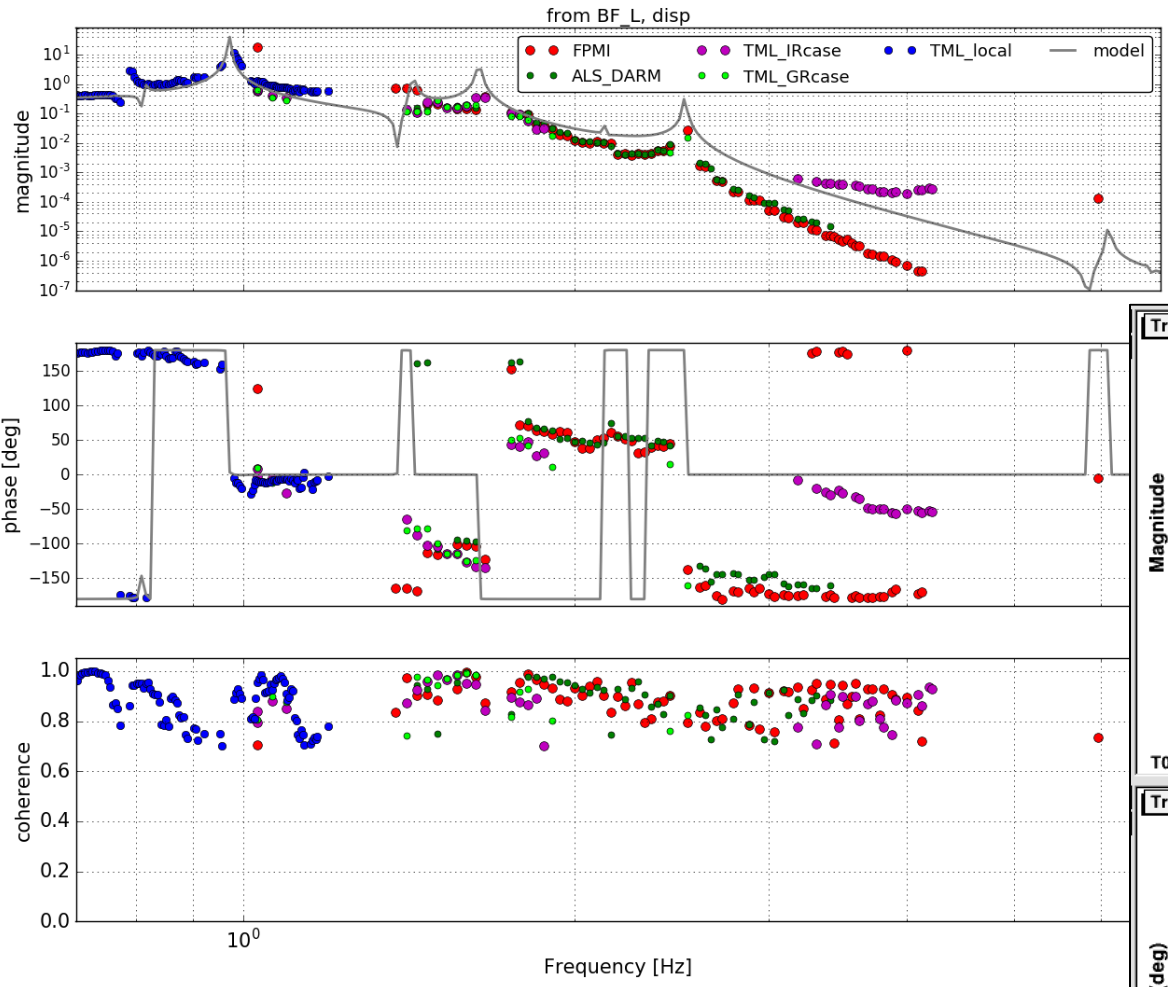
Other ref: https://github.com/YoshinoriFujii/Weekly-task/issues/37

Simulation models:

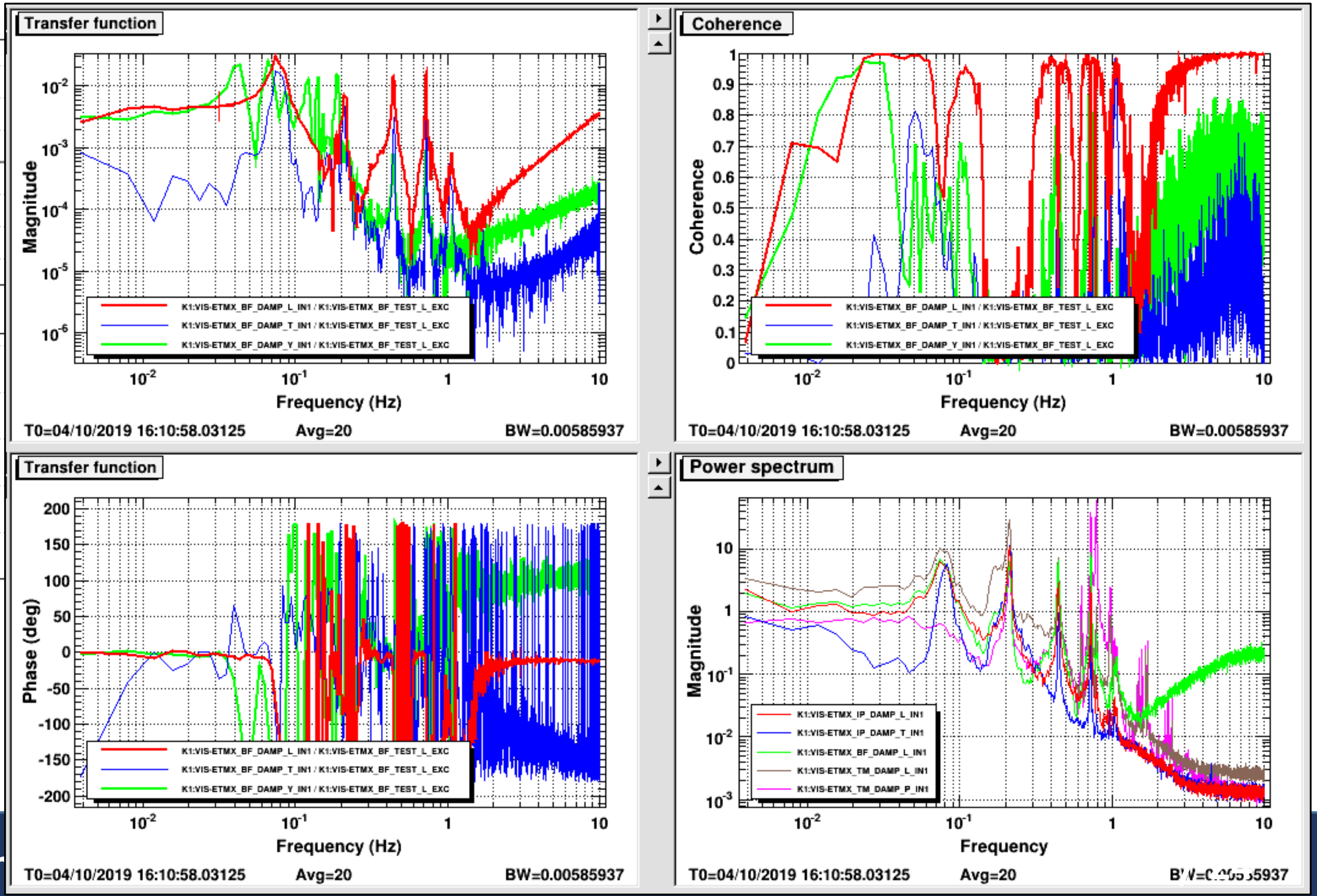




Results: displacement transfer functions, from BFL

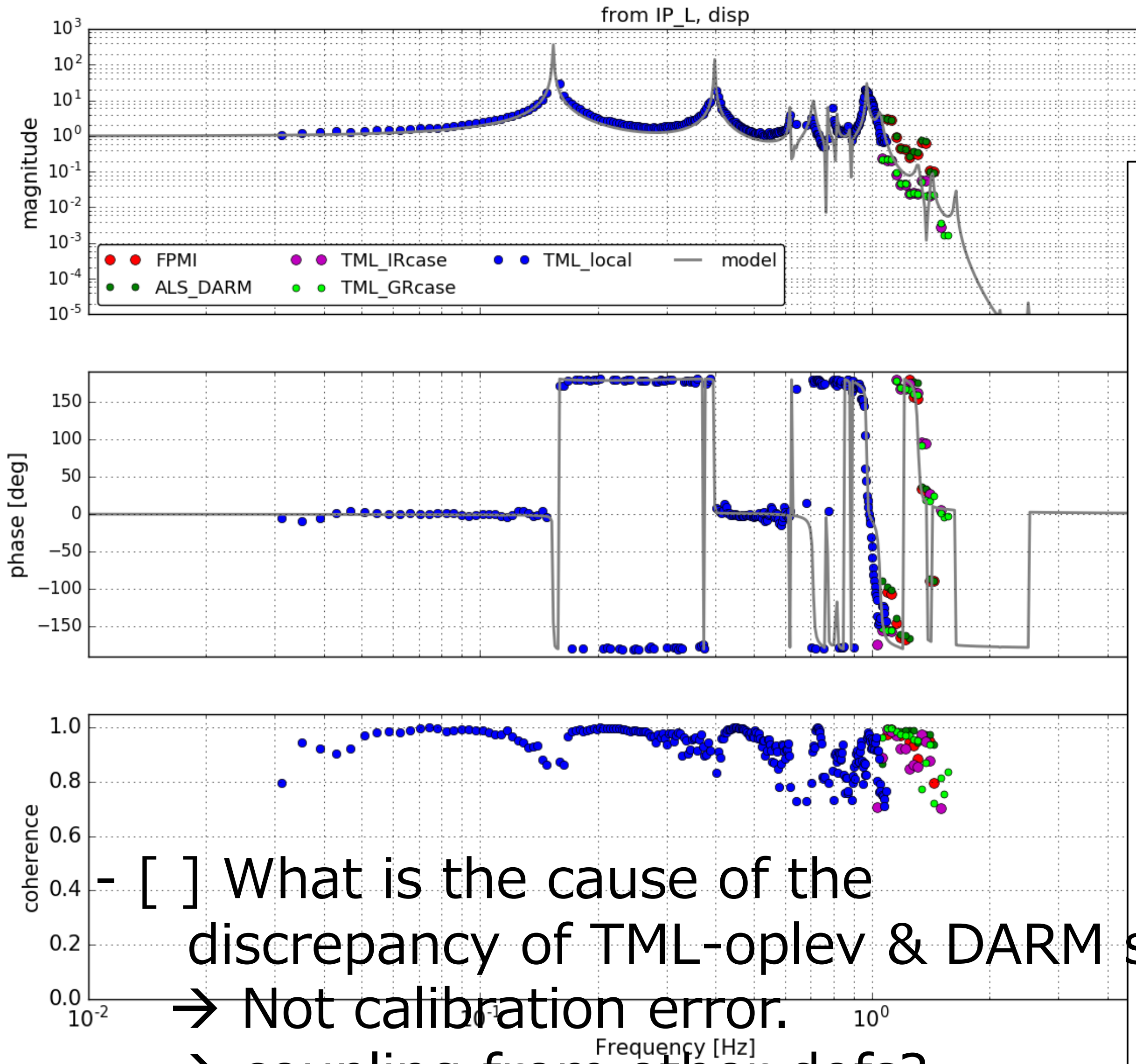


It seems that the discrepancy comes from the issue of LVDT, the direct sensor-actuator coupling.

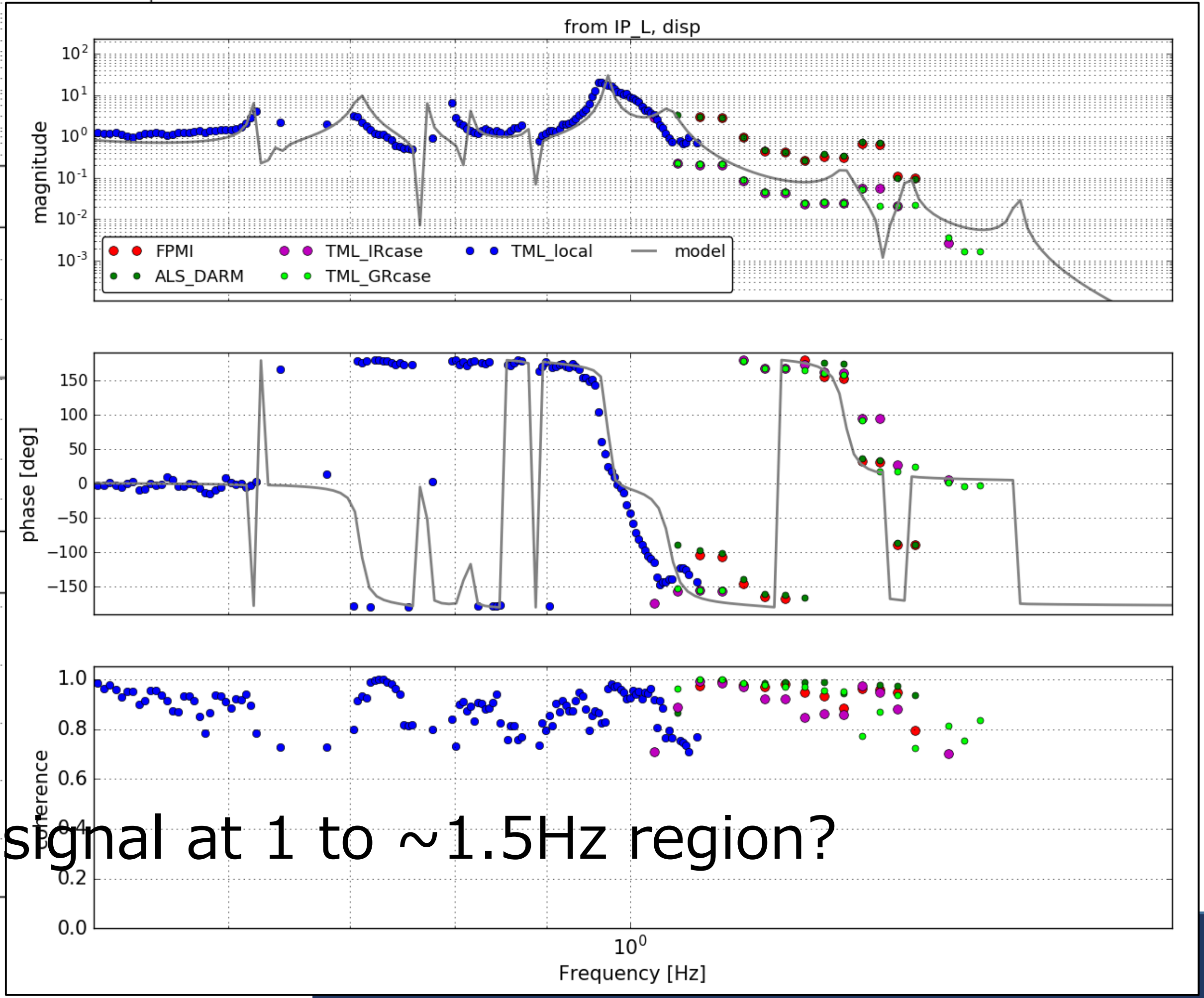


→ Not reliable.

Results: displacement transfer functions, from IPL

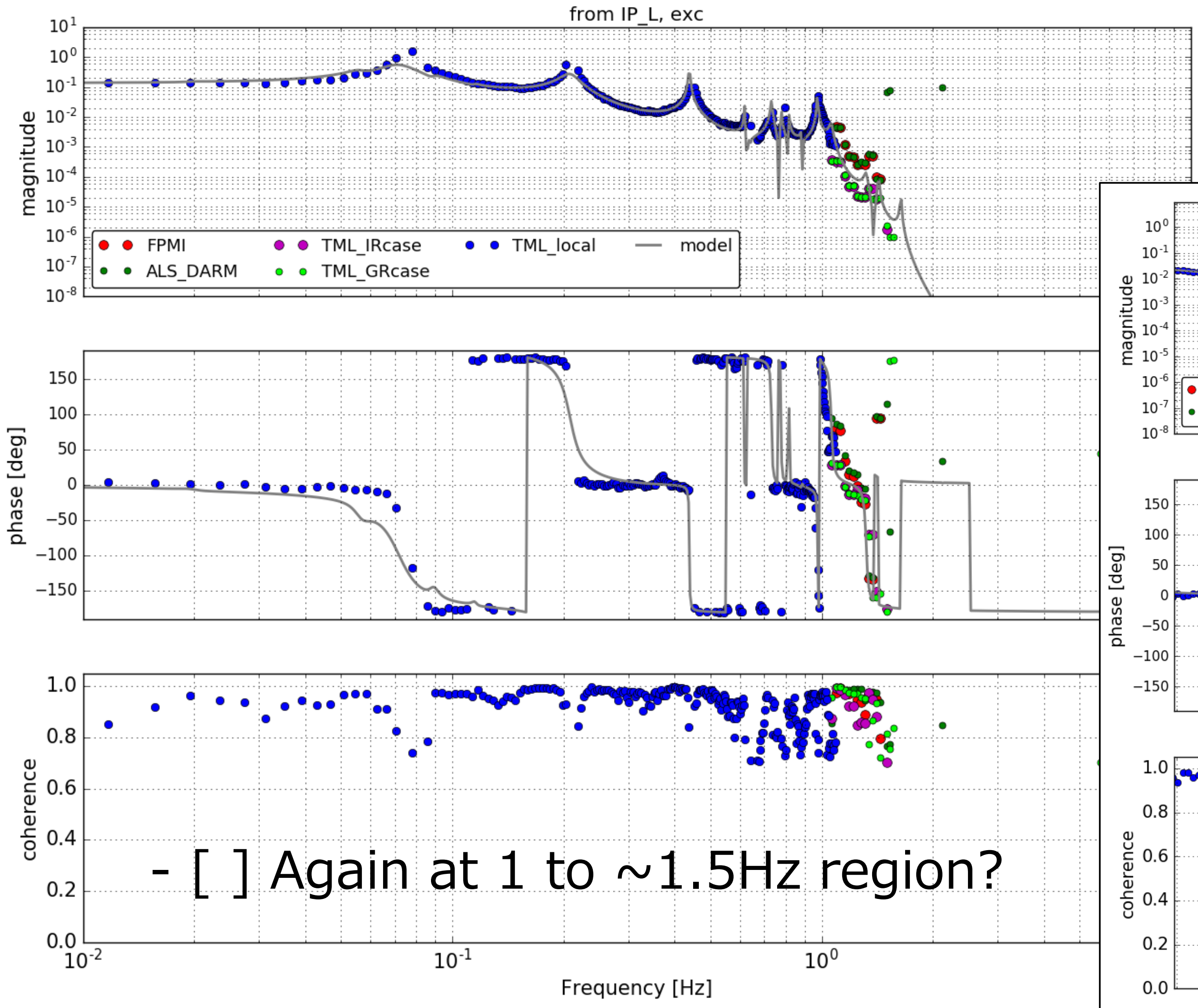


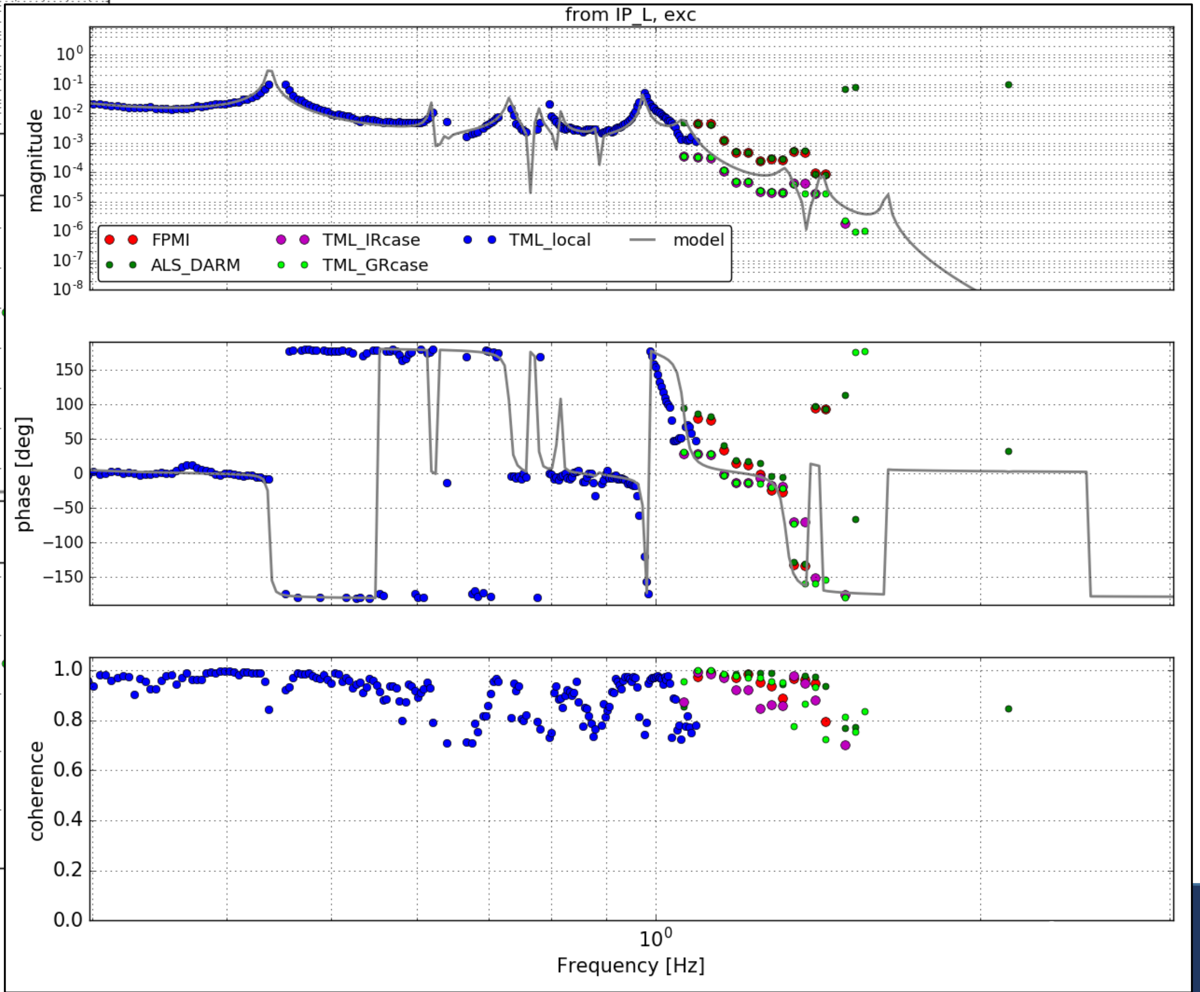
It seems that model have to be tuned at 1 to ~1.5Hz region.



- [ ] What is the cause of the discrepancy of TML-oplev & DARM signal at 1 to ~1.5Hz region?
  → Not calibration error.
  → coupling from other dofs?

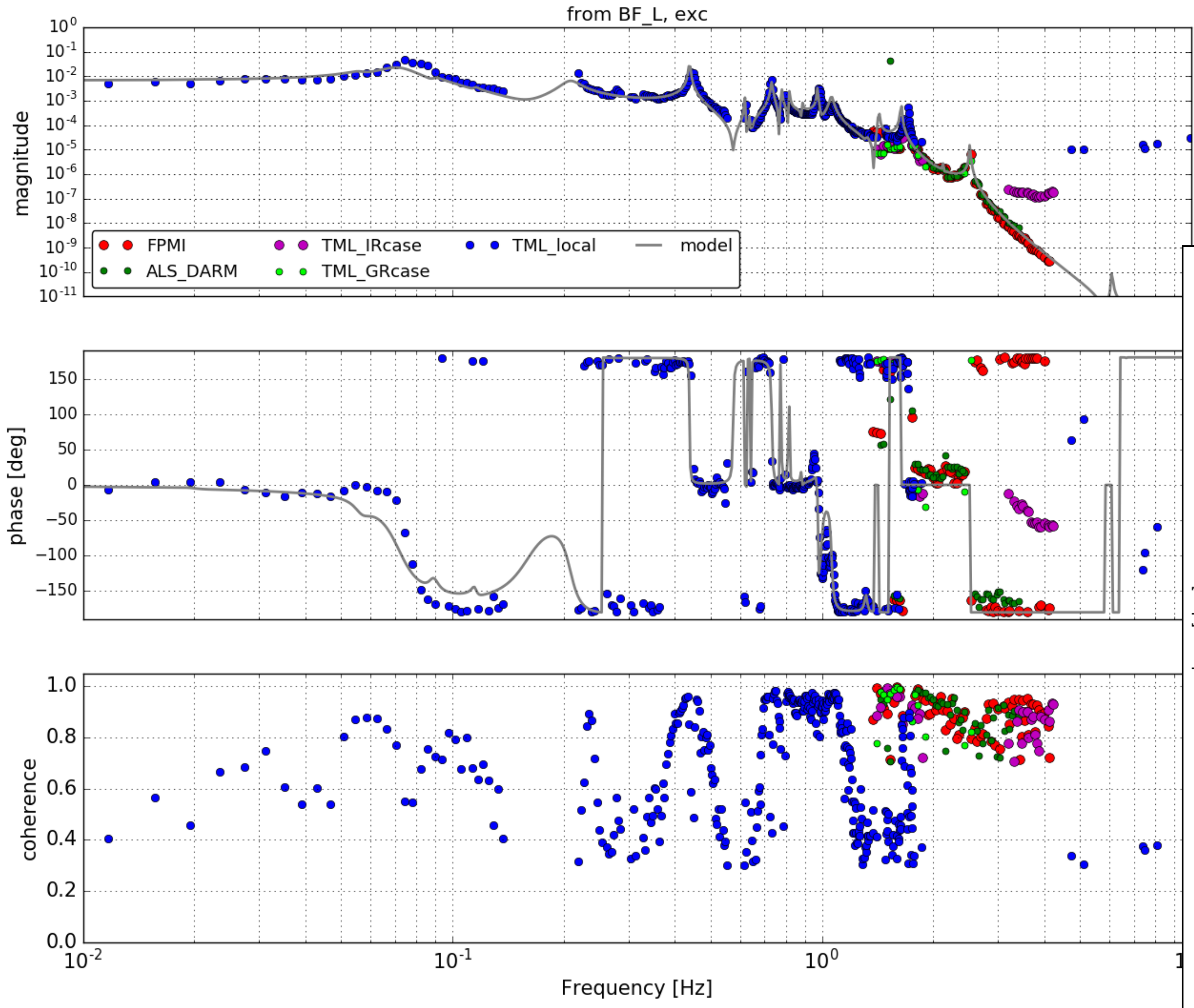
Results: force transfer functions, from IPL



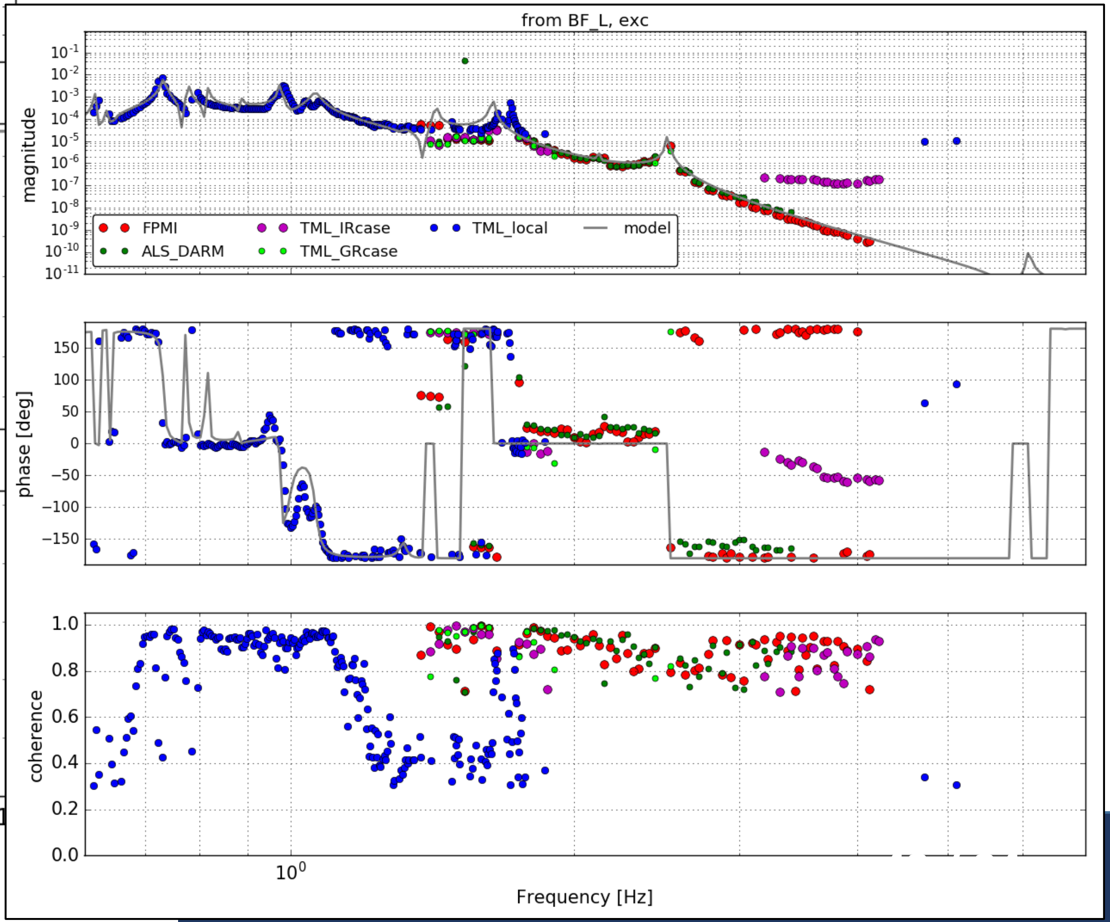


- [ ] Again at 1 to ~1.5Hz region?

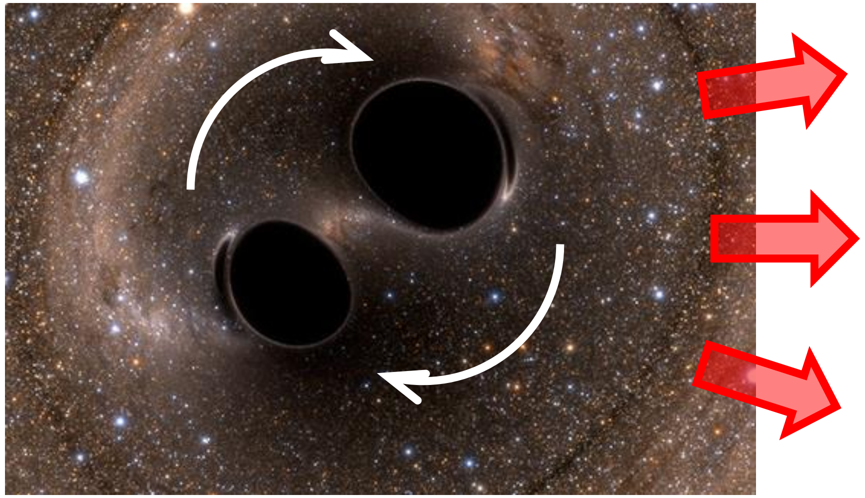
Results: force transfer functions, from BFL

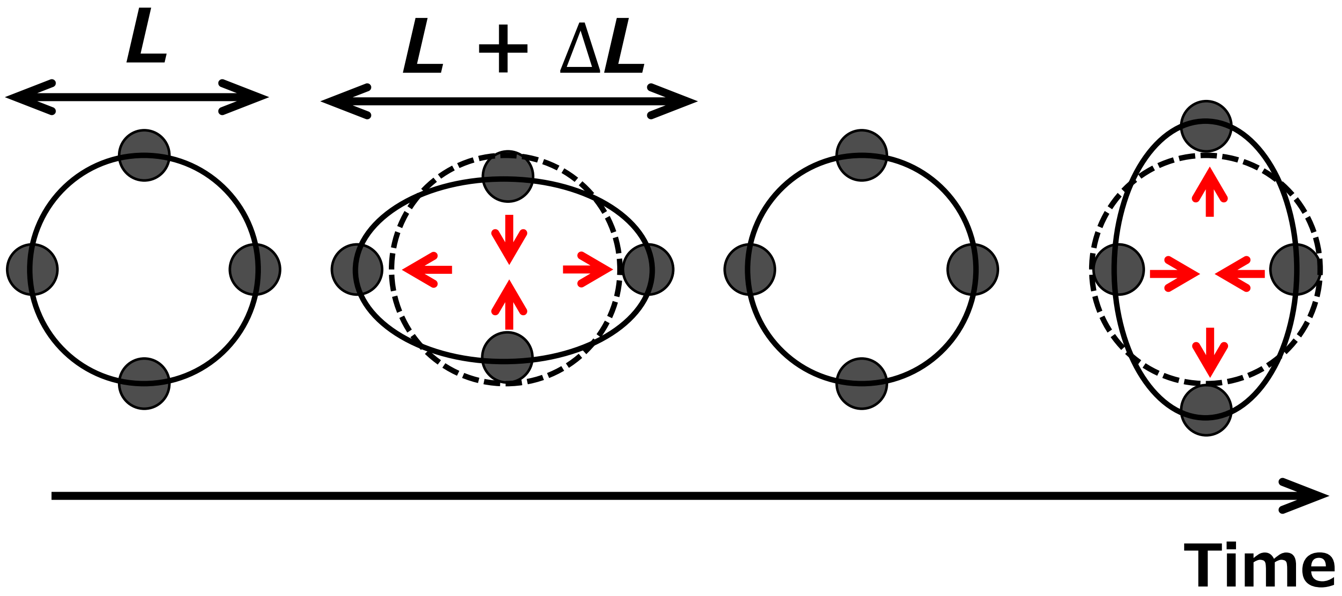


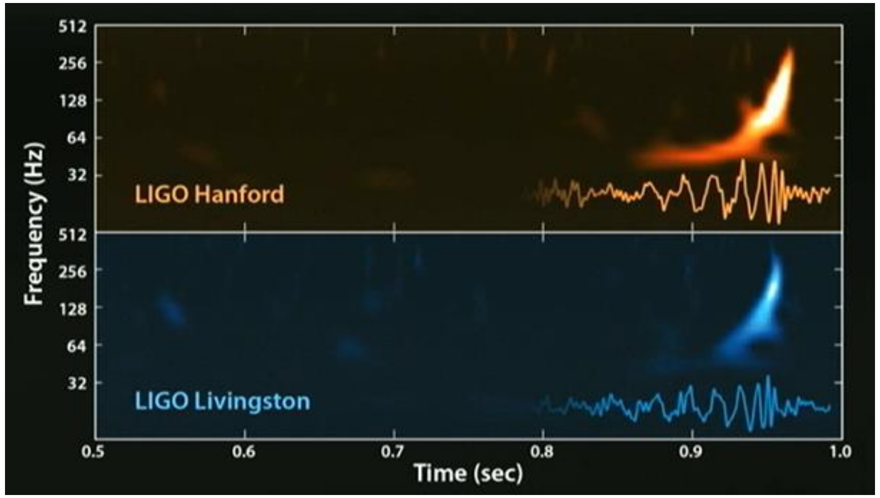
The transfer function up to 4Hz was agree with the model.



重力波?



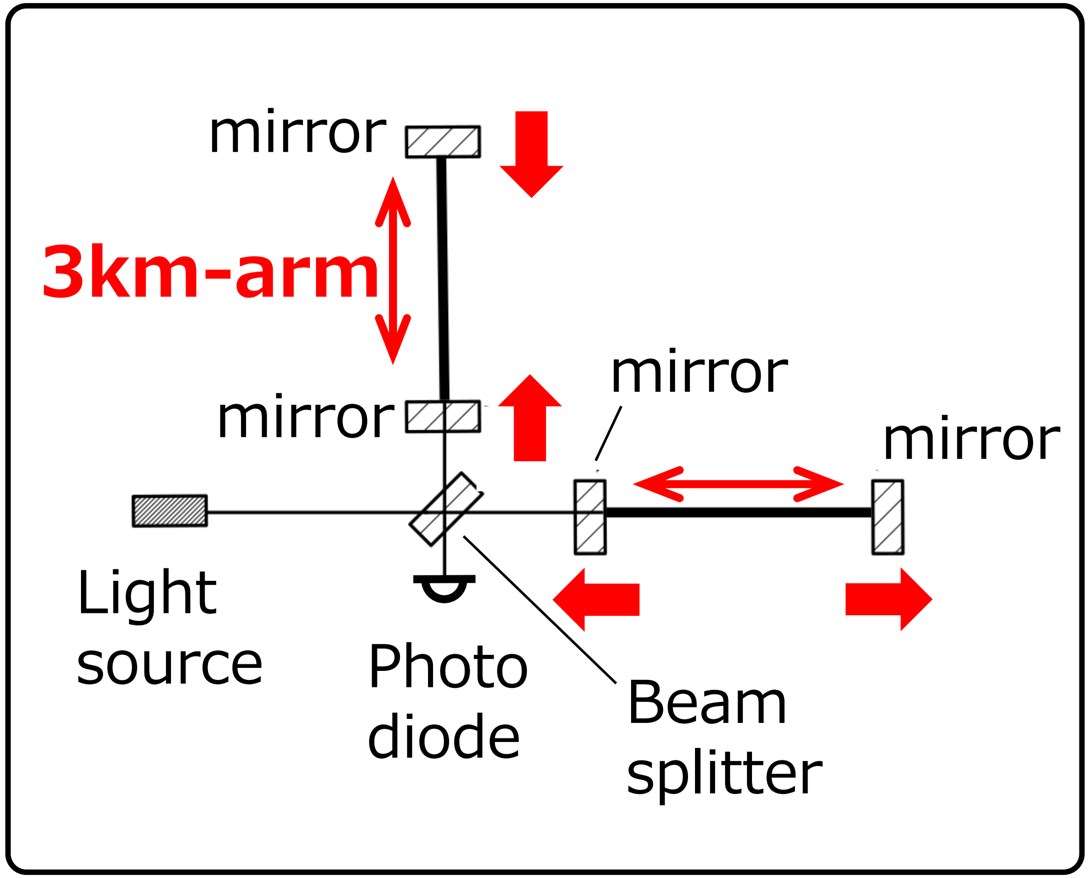




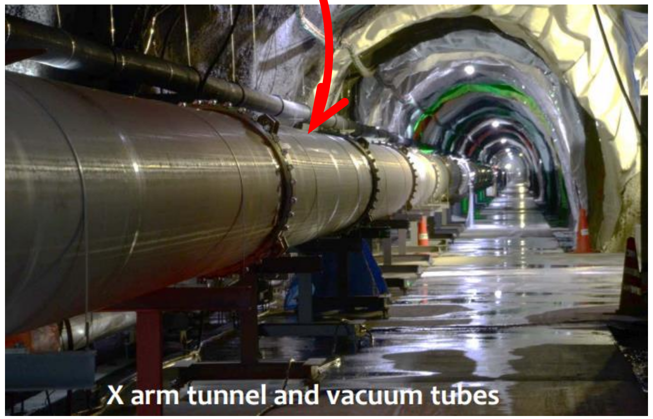
- 2015.9.14 初検出!
- BBH, BNS 検出!

→ **新しい天文学!**

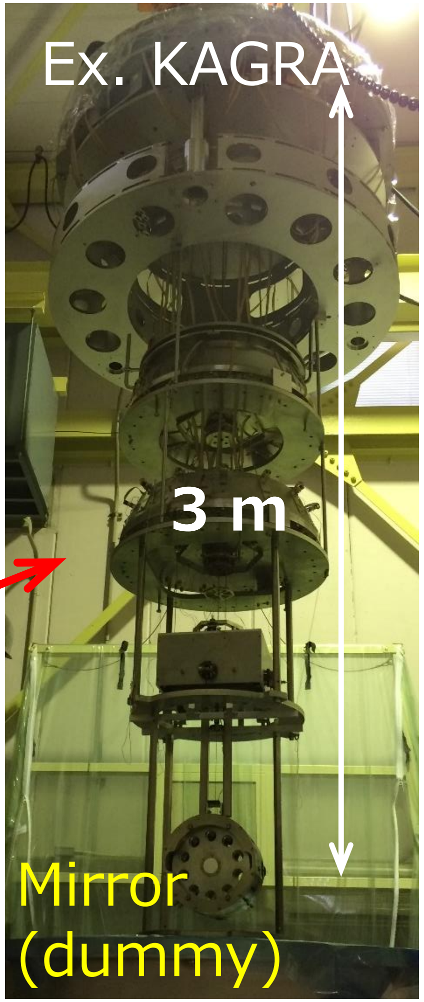
重力波検出器と、サスペンション



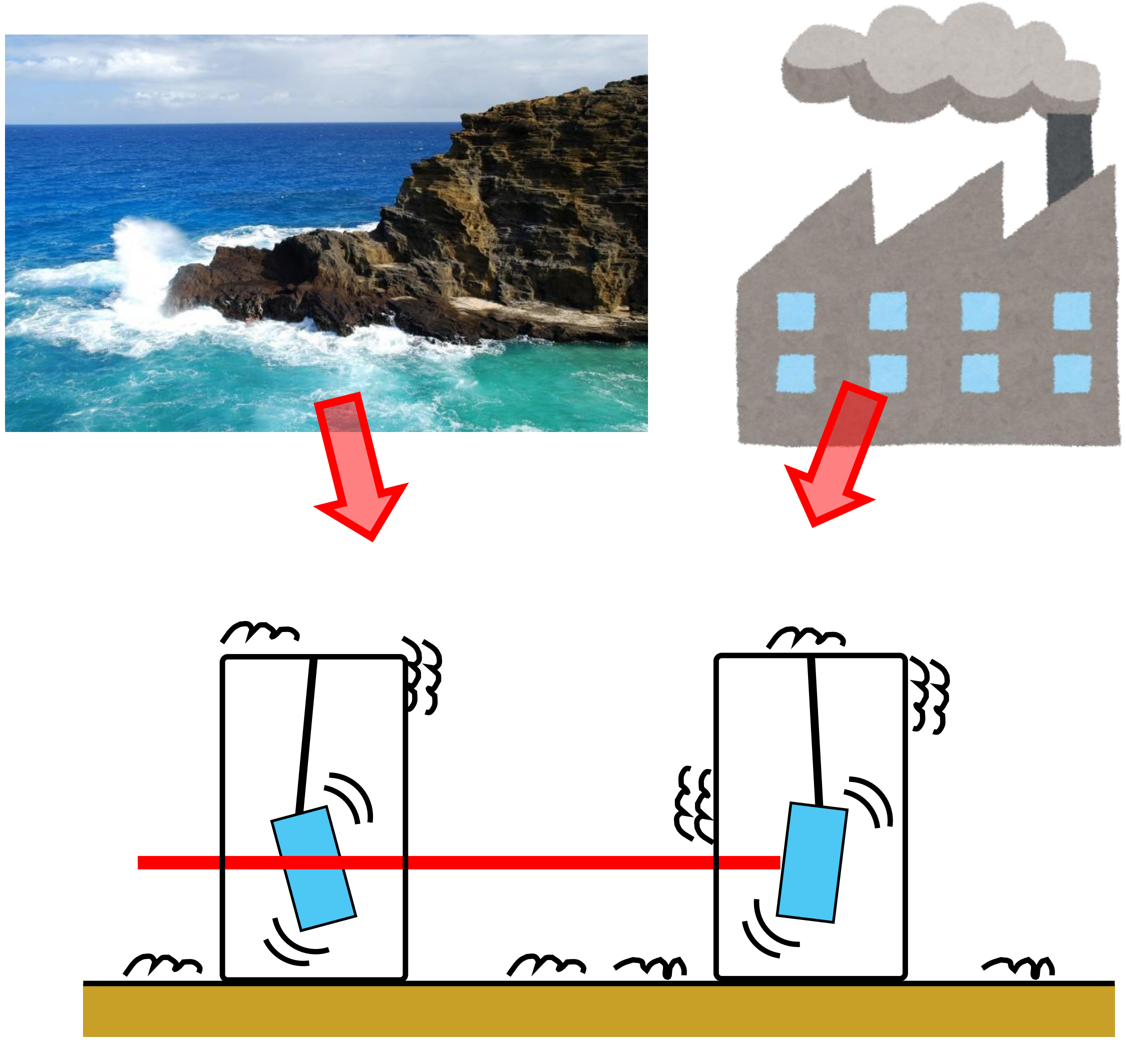
1) Michelson-based interferometer
2) Fabry-Perot cavities
3) 3km-arm

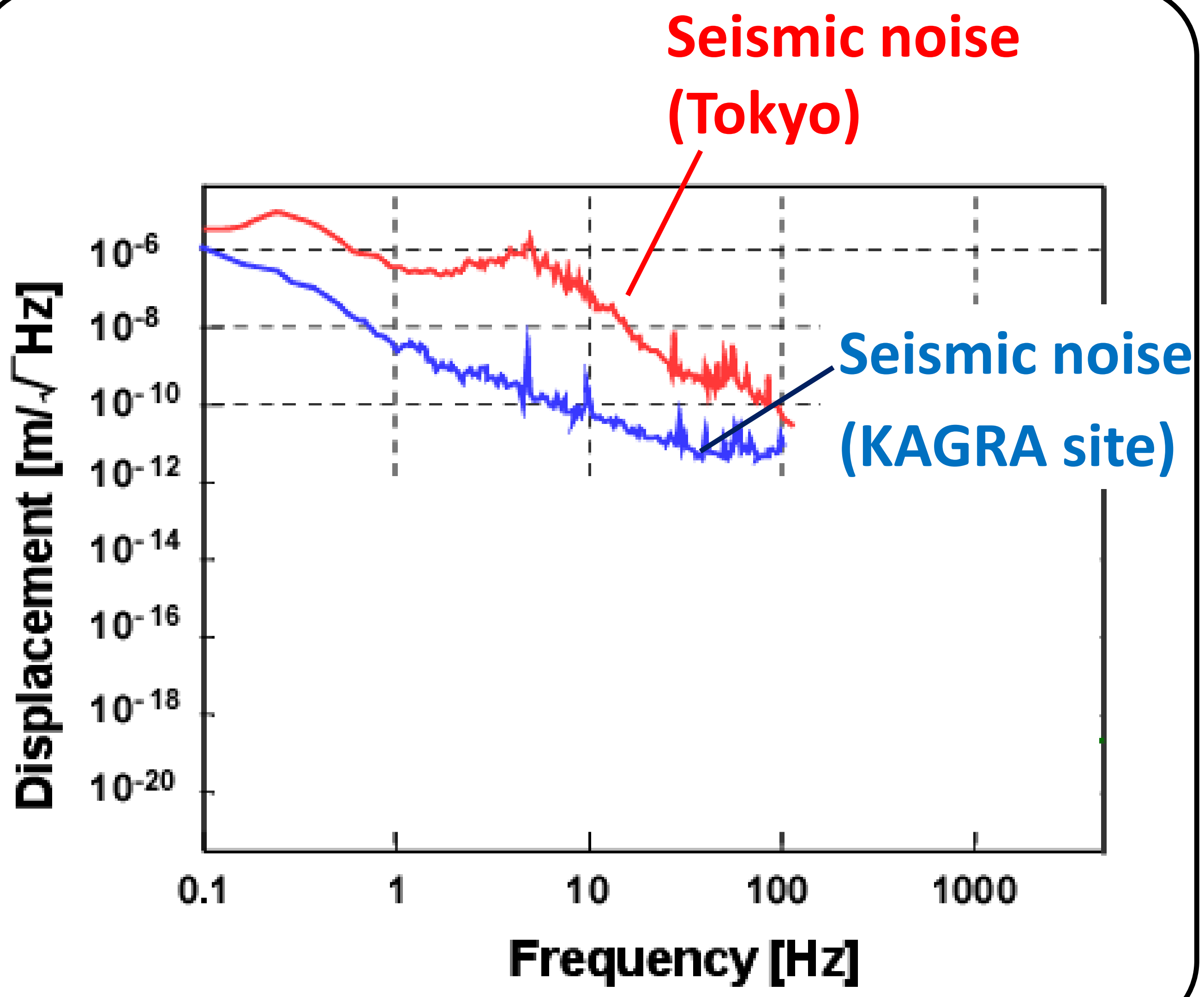


4) Suspended core optics



地面振動雑音

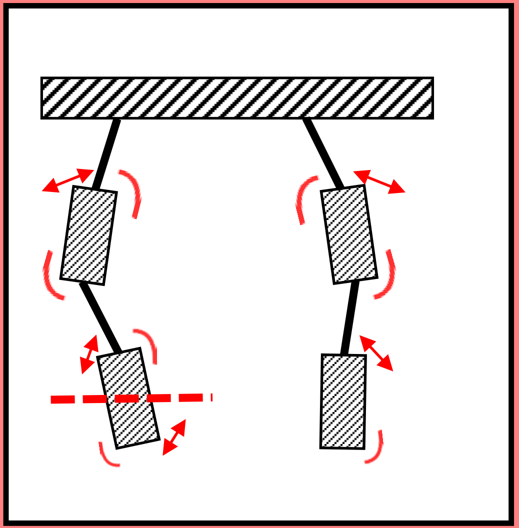




Seismic noise
(Tokyo)
Seismic noise
(KAGRA site)
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
Displacement [m/√Hz]
0.1
1
10
100
1000
Frequency [Hz]

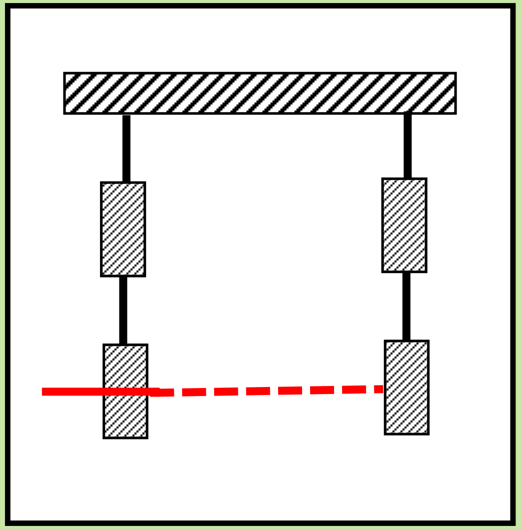
Designing active control system / Control phase

1. Calm-down phase



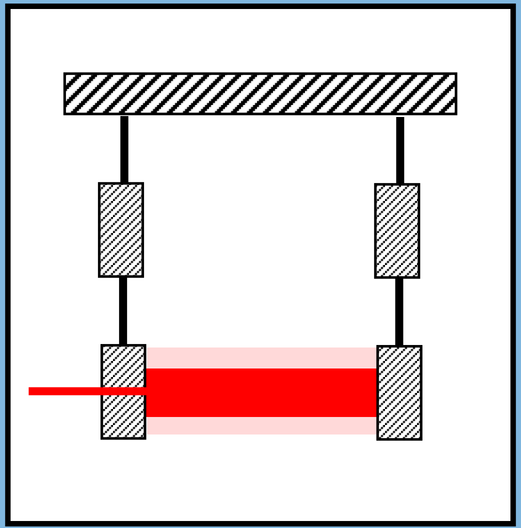
Suppress
large disturbance

2. Lock-acquisition phase



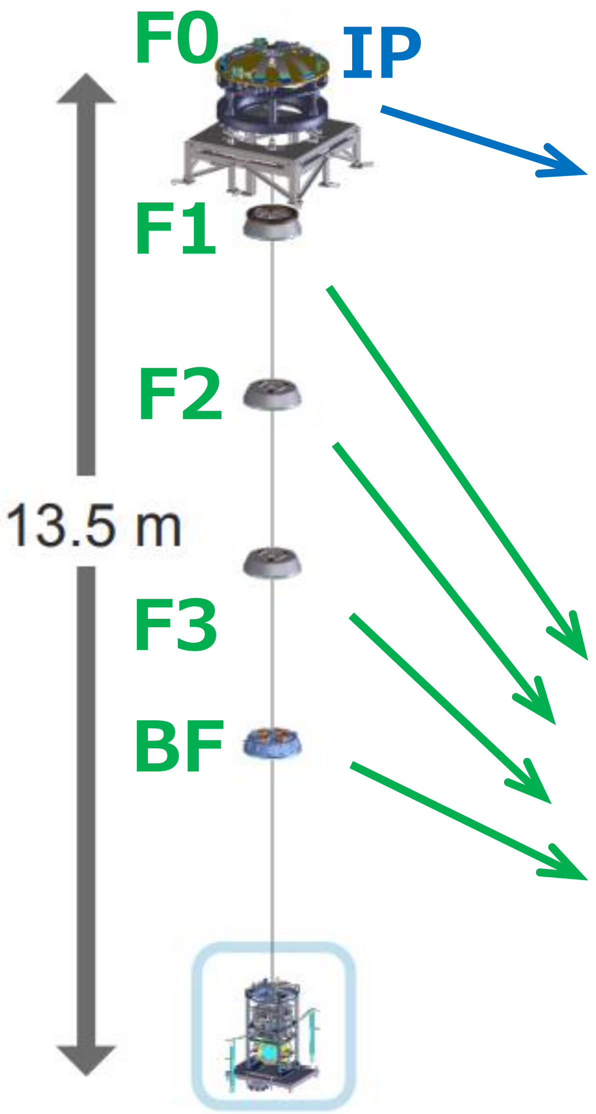
Reduce RMS velocity
RMS angle
(Root-Mean-Square)

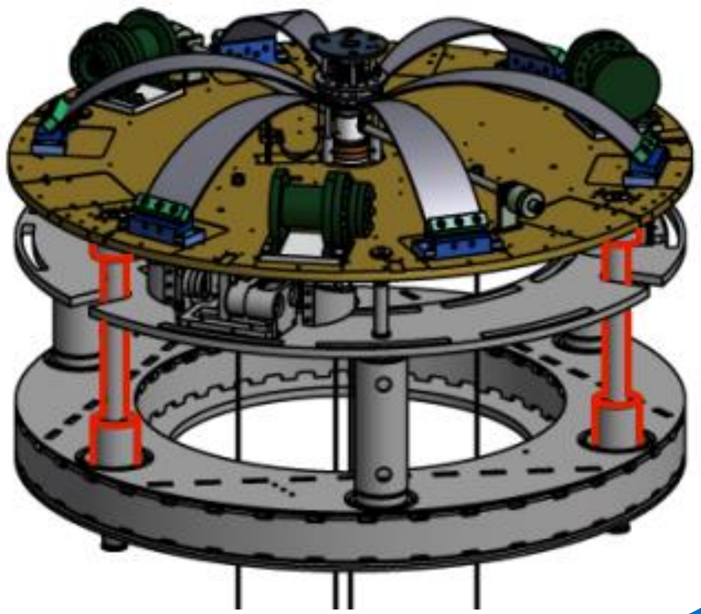
3. Observation phase



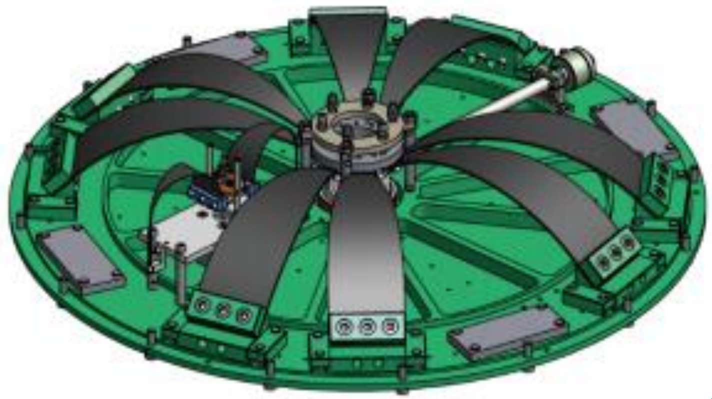
Keep position
with low noise
control

メイン鏡用の防振装置



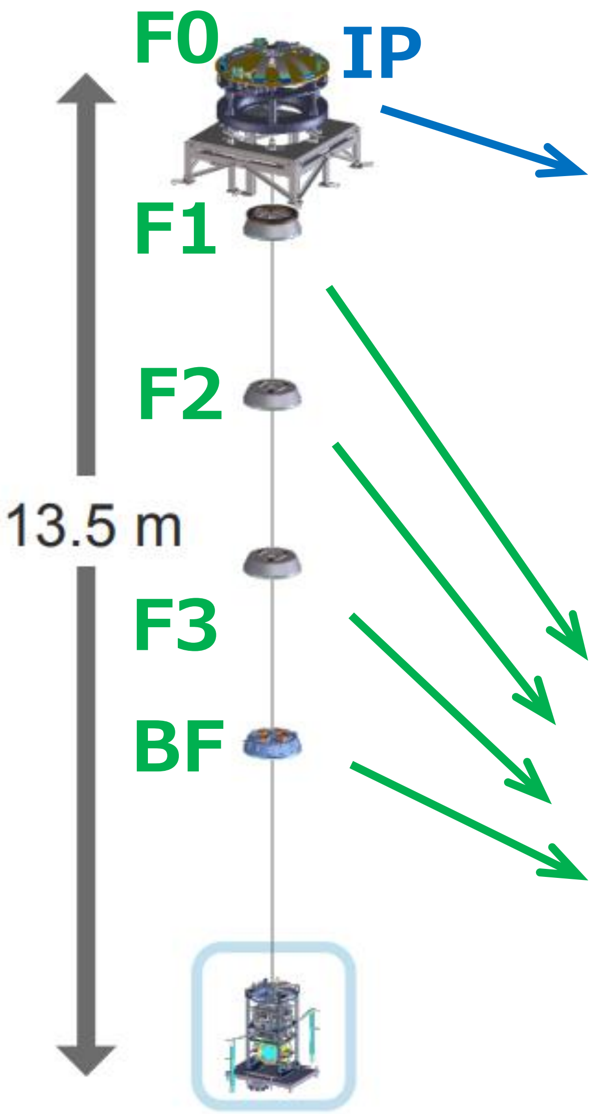


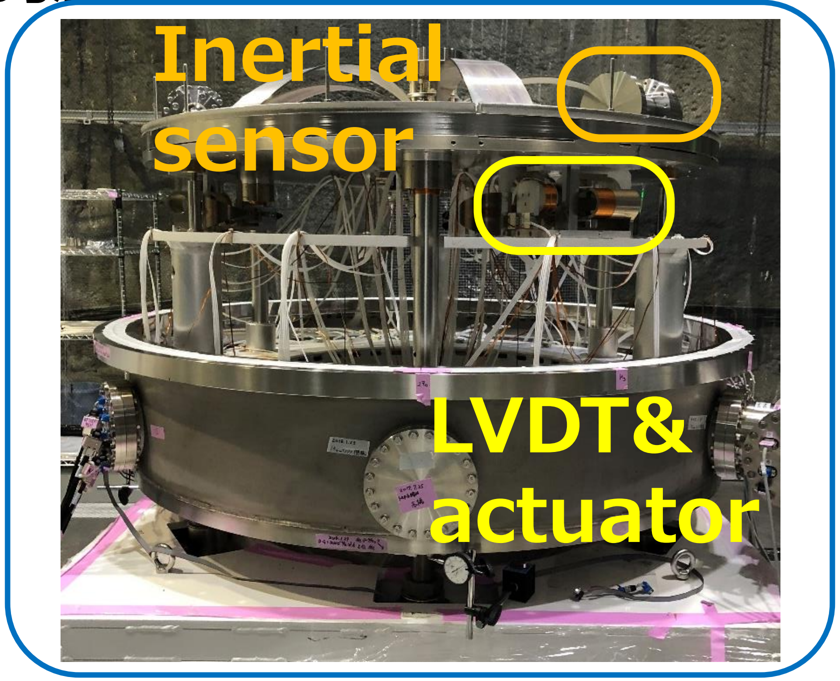
Inverted Pendulum
(~ 70 mHz)



Geometric-Anti Spring
(~ 0.4 Hz)

メイン鏡用の防振装置



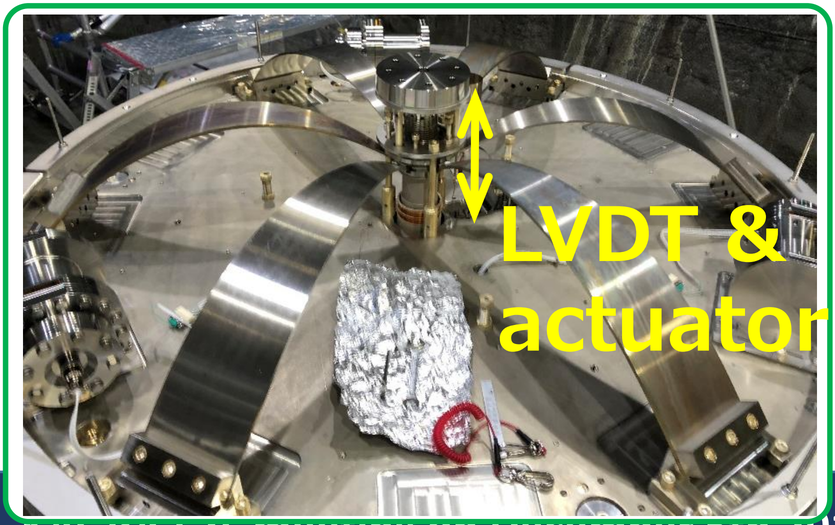


Inverted Pendulum

with 3 horizontal

-- LVDT & actuator units

-- inertial sensors



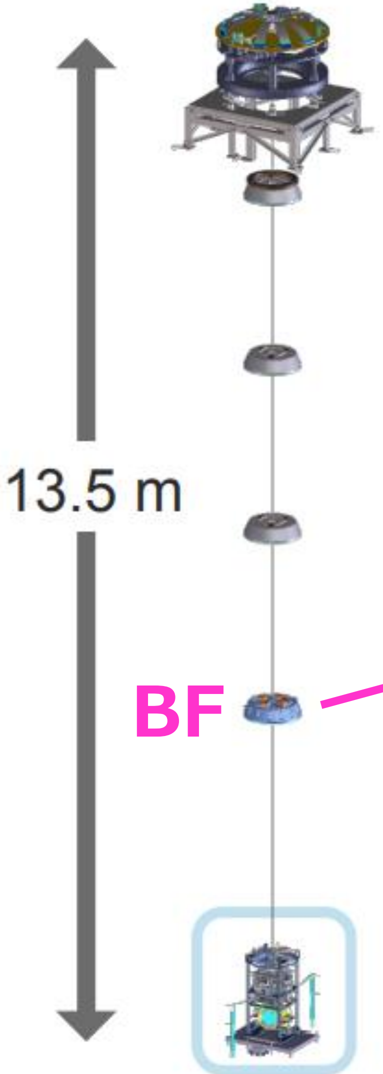
Geometric-Anti Spring

with 1 vertical

LVDT & actuator unit

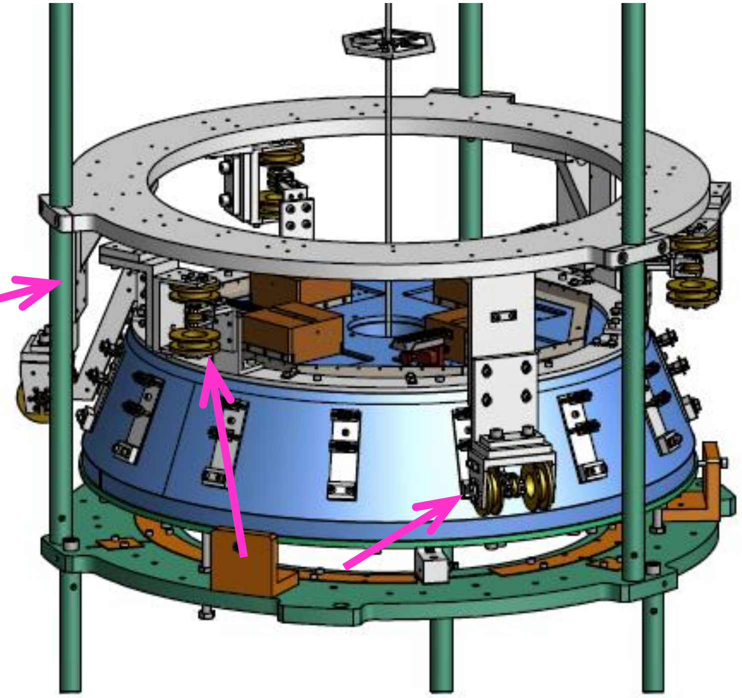
メイン鏡用の防振装置

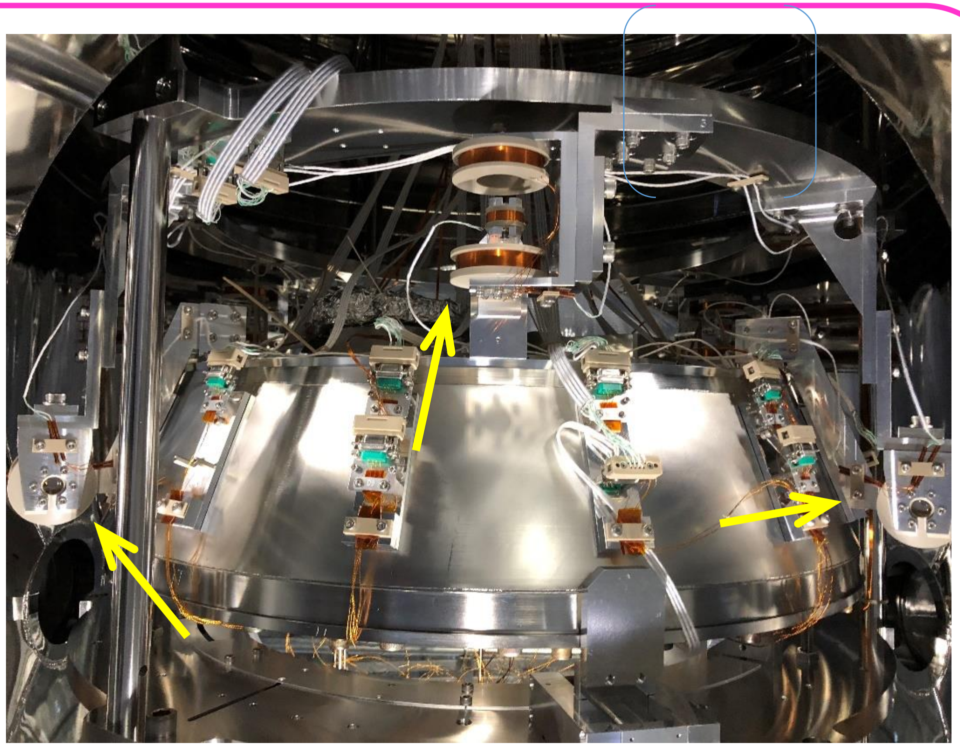
(イタリアのグループの協力のもと開発)



Bottom-Filter DAMPER

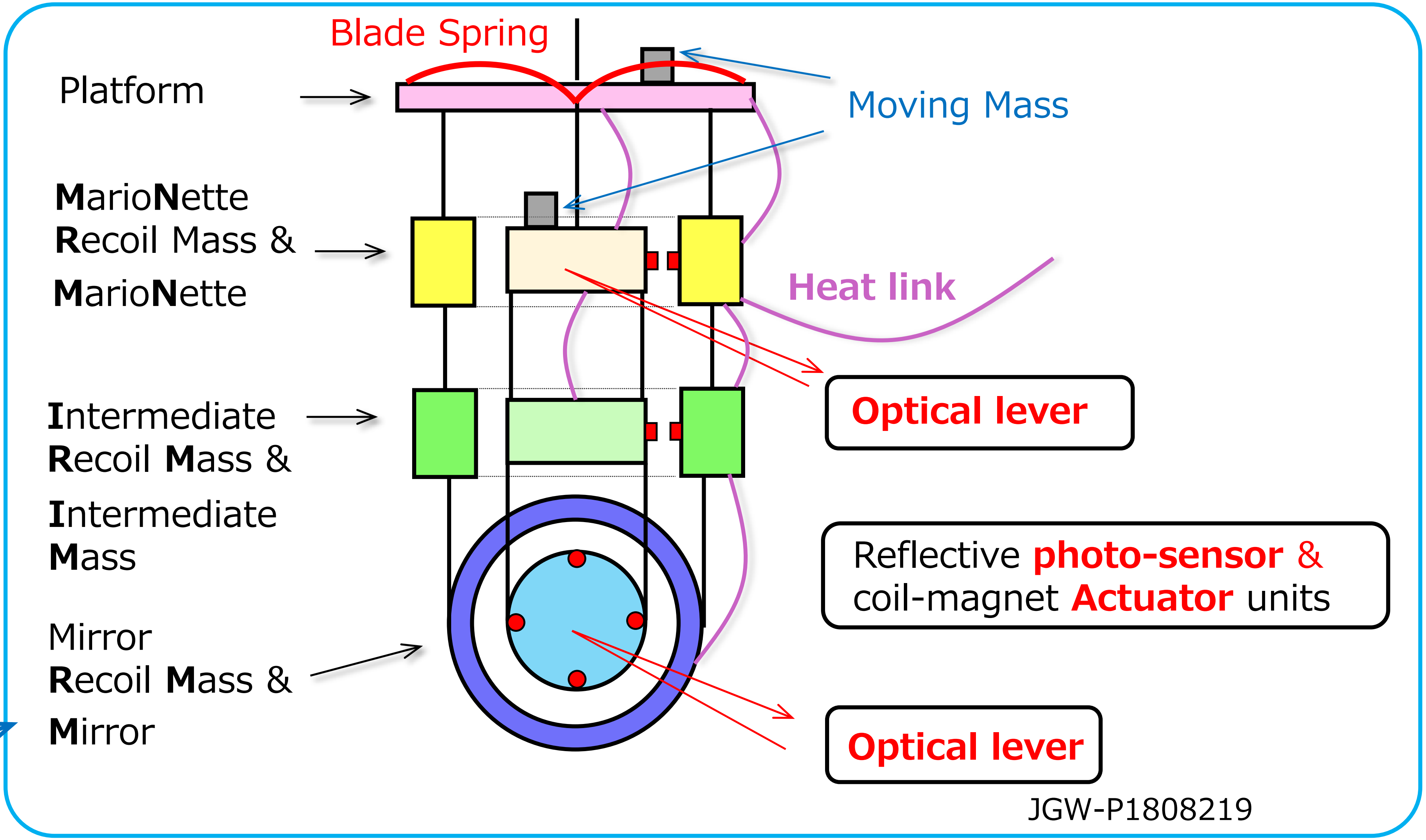
with 3 horizontal & 3 vertical LVDT & actuator units



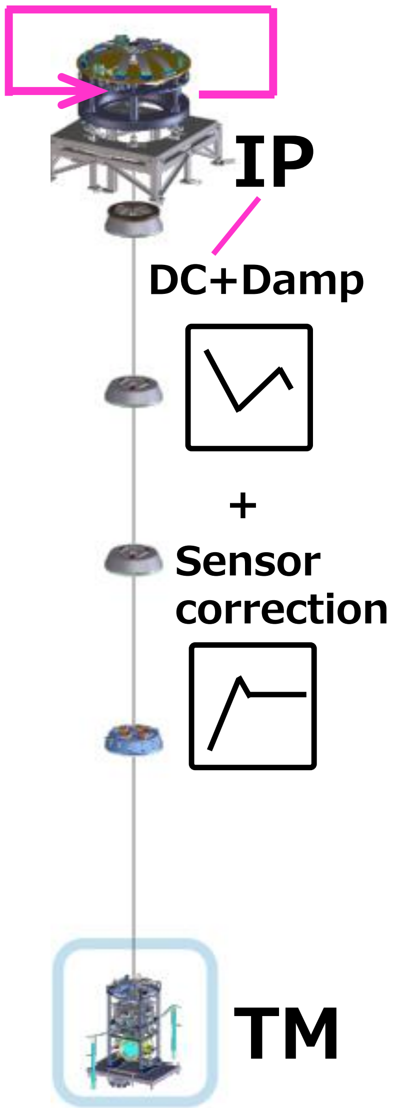


メイン鏡用の防振装置

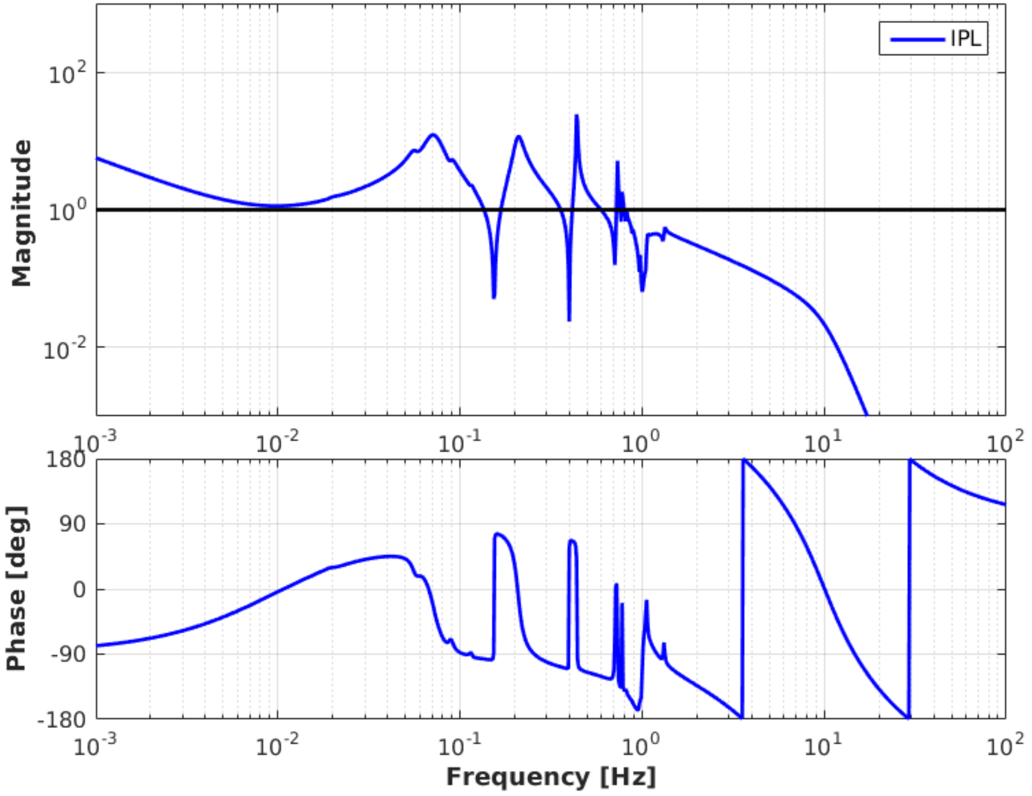

13.5 m


Blade Spring
Platform
Moving Mass
MarioNette
Recoil Mass &
MarioNette
Heat link
Optical lever
Intermediate
Recoil Mass &
Intermediate
Mass
Reflective photo-sensor &
coil-magnet Actuator units
Mirror
Recoil Mass &
Mirror
Optical lever
JGW-P1808219

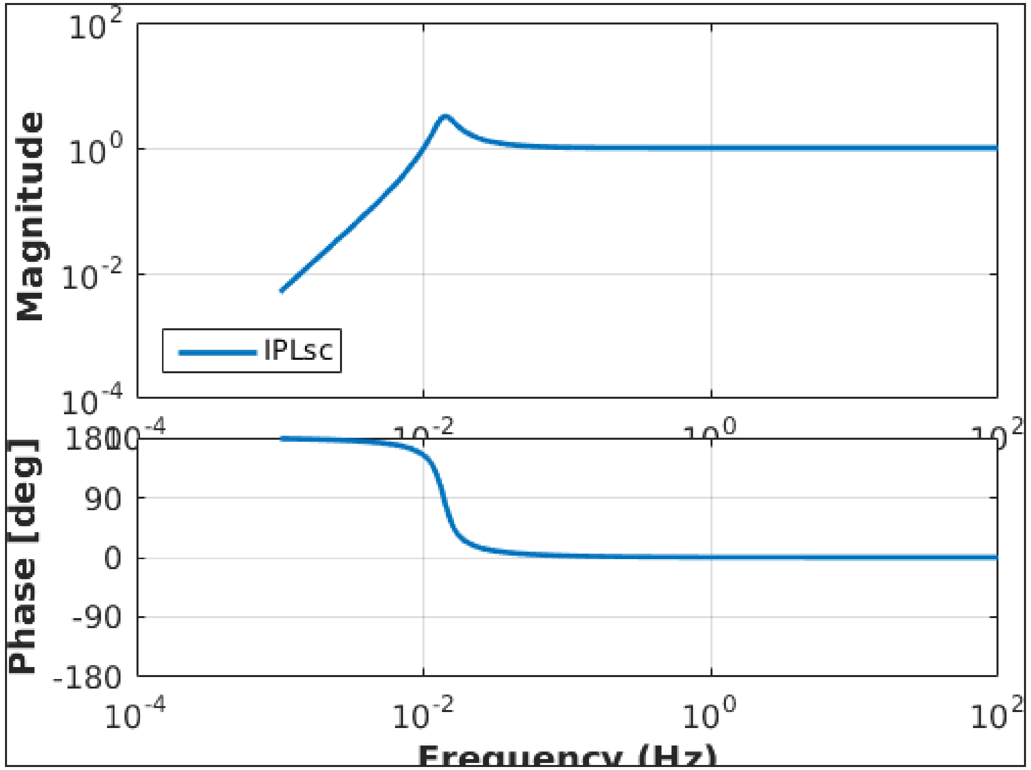
制御ループ at IP-stage:



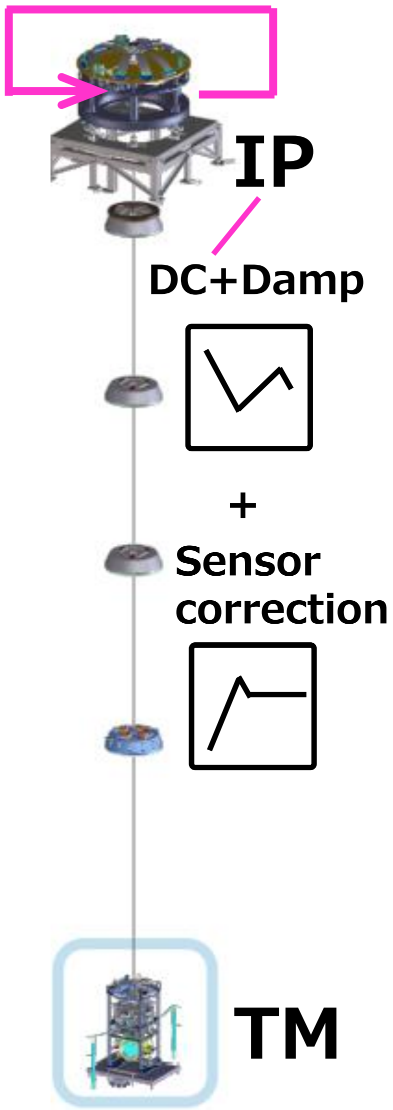
1. OLTF for IP-LVDT

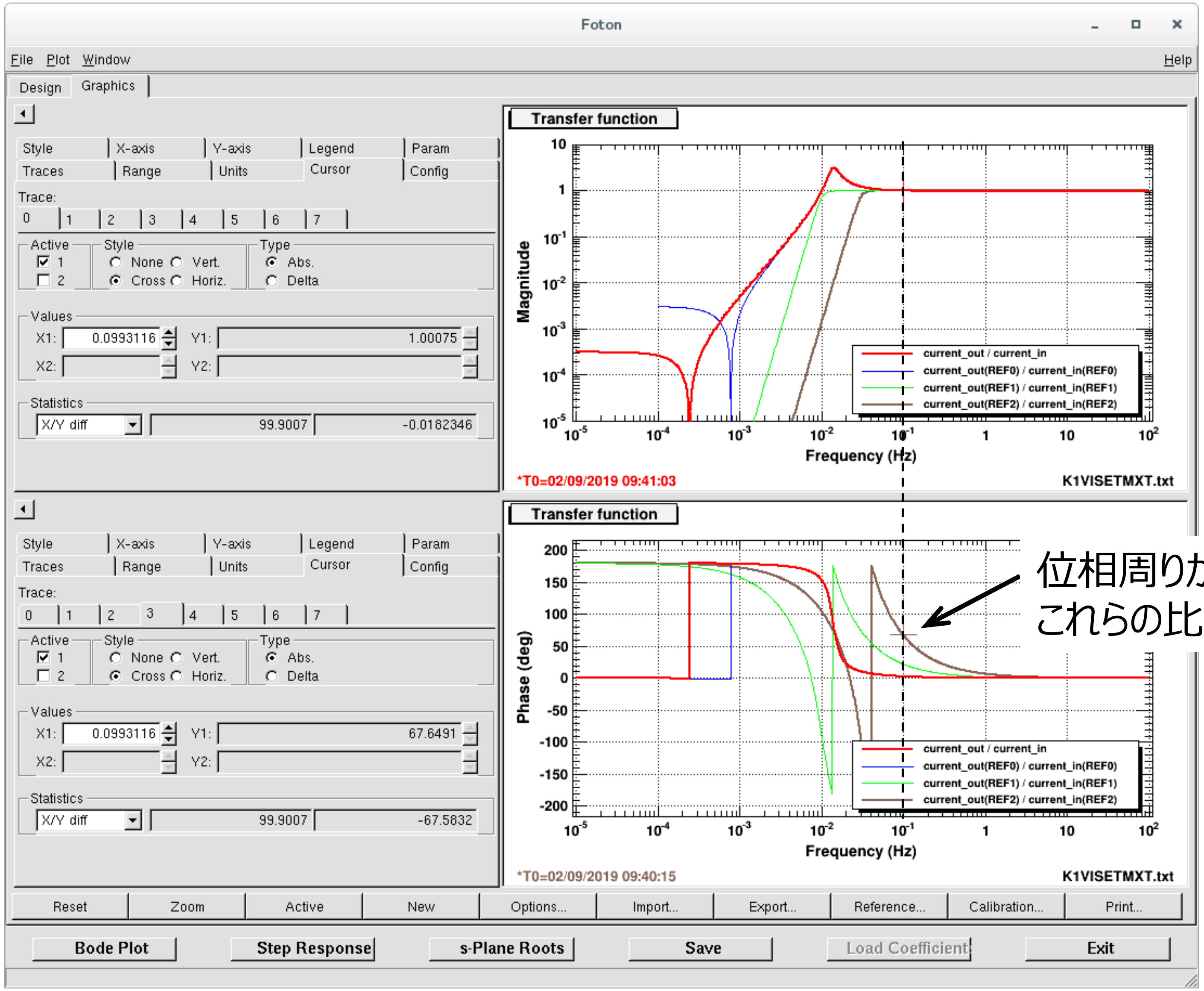


2. Sensor correction filter



Sensor correction filter の検討

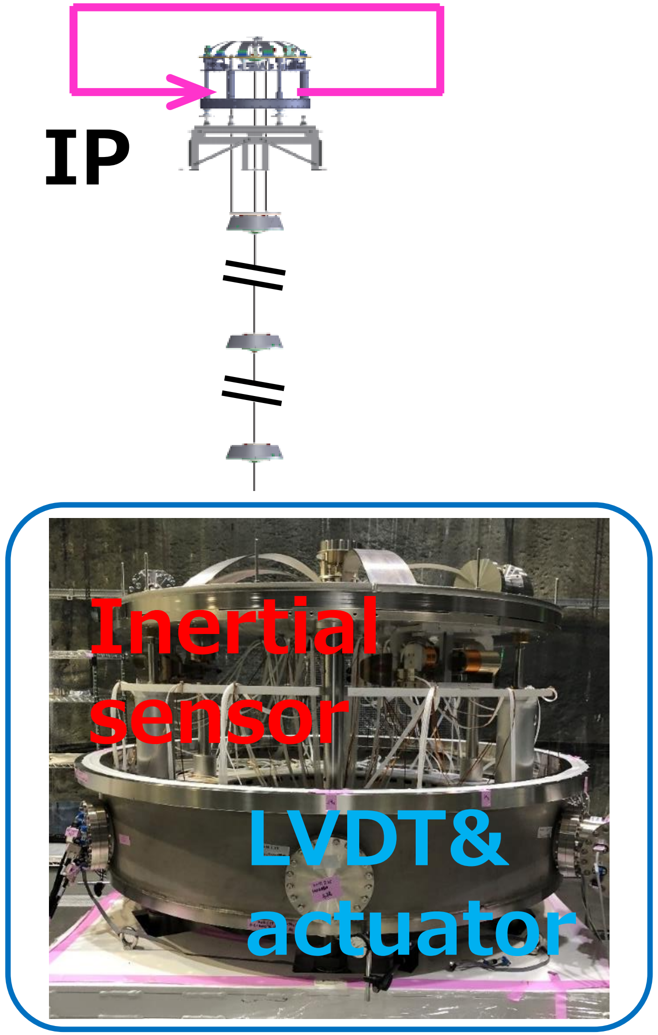


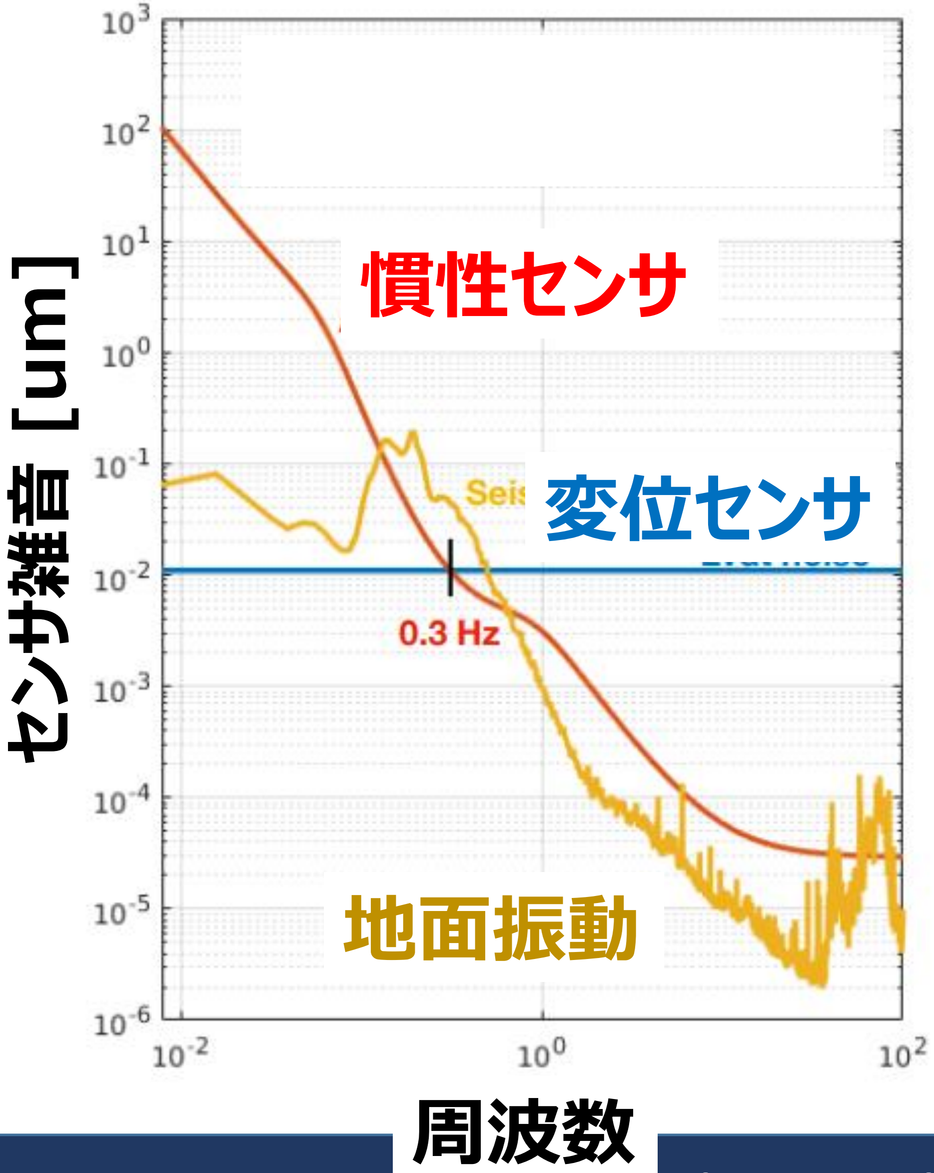


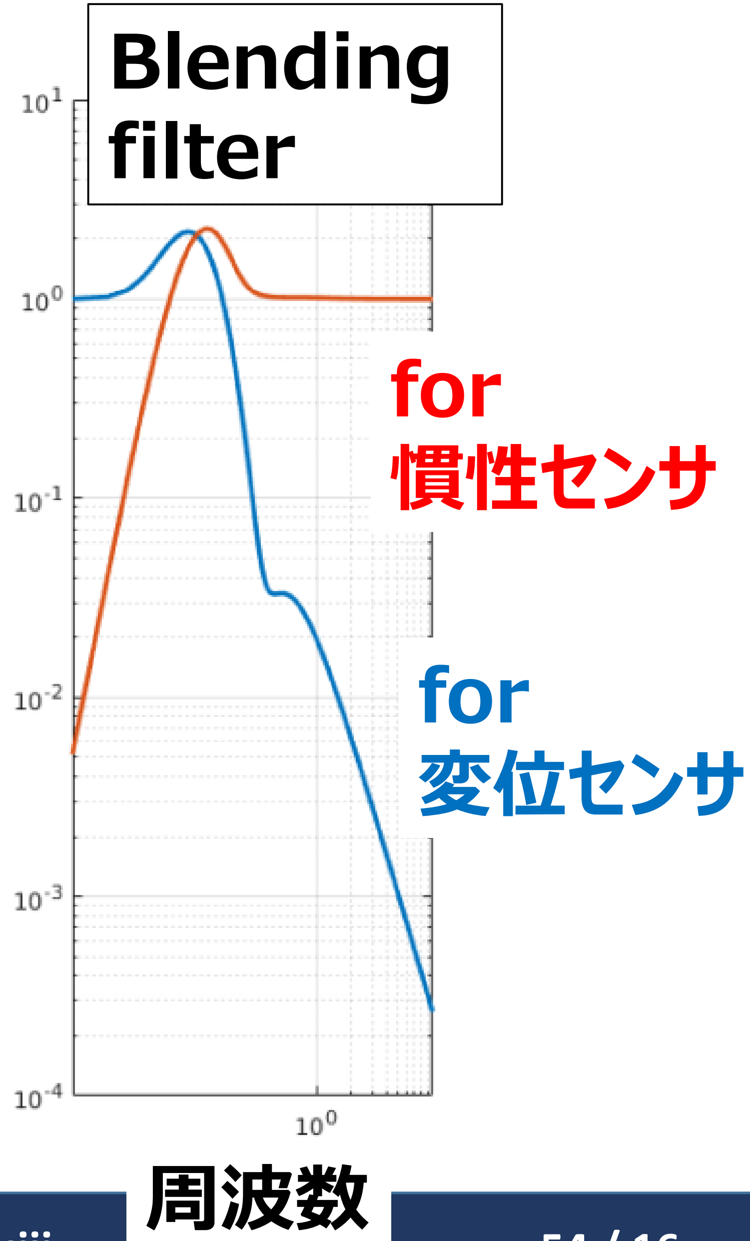
位相周りがなるべく少ないものを採用した。
これらの比較plotを作成しておく。

Sensor blending & inertial damping

(From JGW-G1909932)







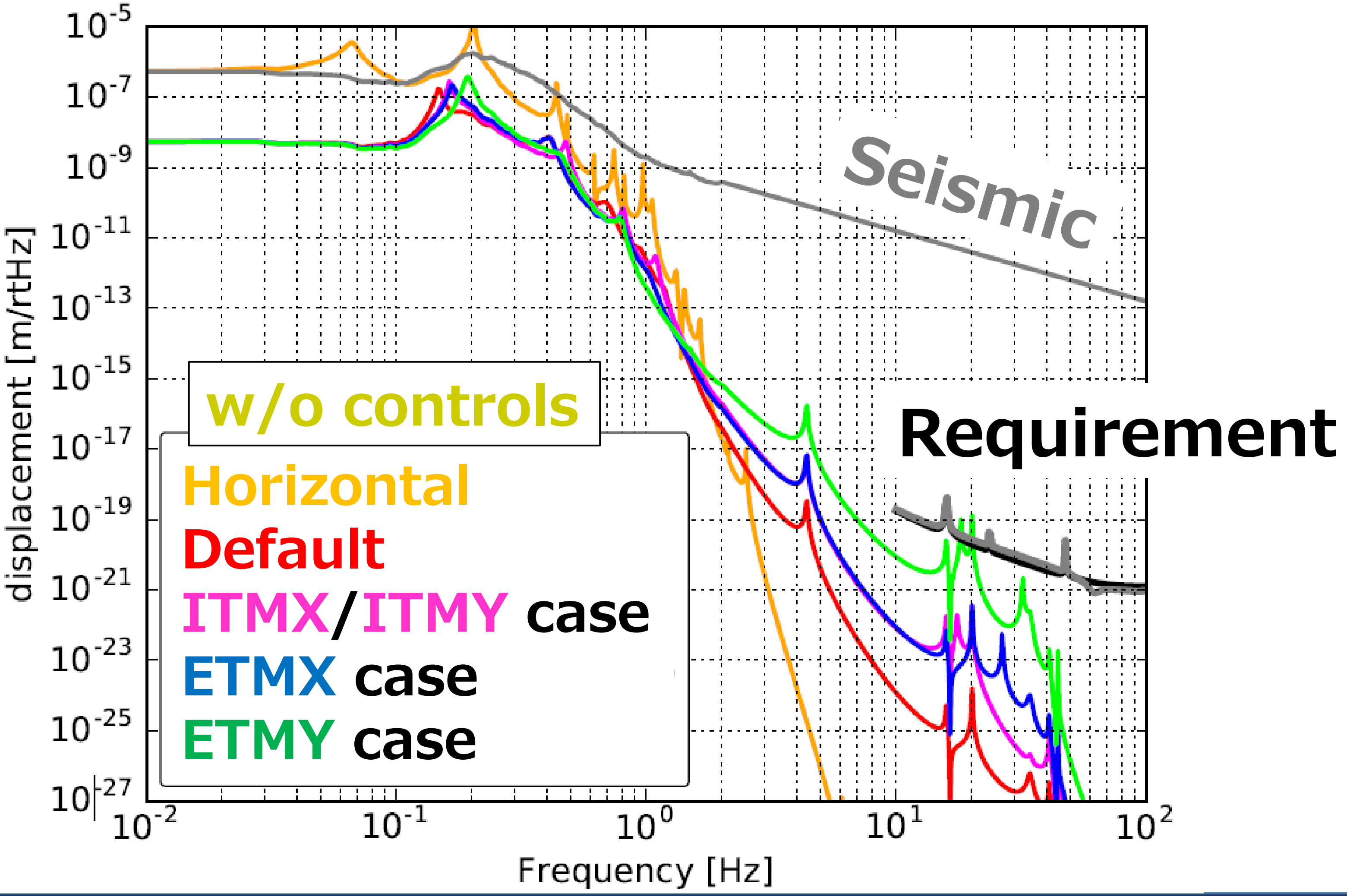
Requirements, Type-A suspensions

Calm-down phase		
Item	Requirement	For/Determined by
$1/e$ modal decay time	< 1 min	Quick recovery
RMS displacement (L)	$< 50\ \mu$m	Smooth transition to next phase
RMS displacement (T, V)	< 0.1 mm	Miscentering
RMS angle (P, Y)	$< 50\ \mu$m	Smooth transition to next phase
Lock acquisition phase		
Item	Requirement	For/Determined by
RMS velocity (L)	$< 240\ \mu$m/s	Auxiliary laser locking
RMS displacement (T, V)	< 0.1 mm	Miscentering
RMS angle (P, Y)	< 880 nrad	Optical gain degradation $< 5\%$
Observation phase		
Item	Requirement	For/Determined by
Displacement noise (L) @ 10 Hz	$< 8 \times 10^{-20}$ m/Hz$^{1/2}$	Sensitivity
Displacement noise (V) @ 10 Hz	$< 8 \times 10^{-18}$ m/Hz$^{1/2}$	Sensitivity (1% coupling to L)
RMS displacement (T, V)	< 0.1 mm	Miscentering
RMS angle (P, Y)	< 200 nrad	Beam spot fluctuation < 1 mm
DC drift (P, Y)	< 400 nrad/h	Sustainable lock for 1 day left

(P, Y) are set as 50 μm and 50 μrad, respectively [28]. The RMS displacement for the other translational DoFs (T, V) are required for another reason which is mentioned shortly later.

Mechanical installation has done! HOWEVER ..

According to a simulation, assuming 1% coupling,

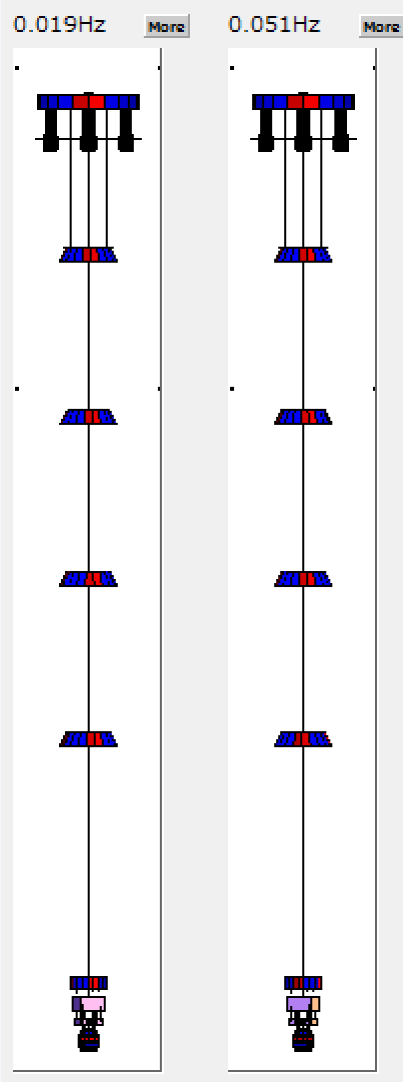


"acceptable
for the O3-run"

(should be)

Note:
-- Modeled w/o Heat-links
-- params are not tuned.

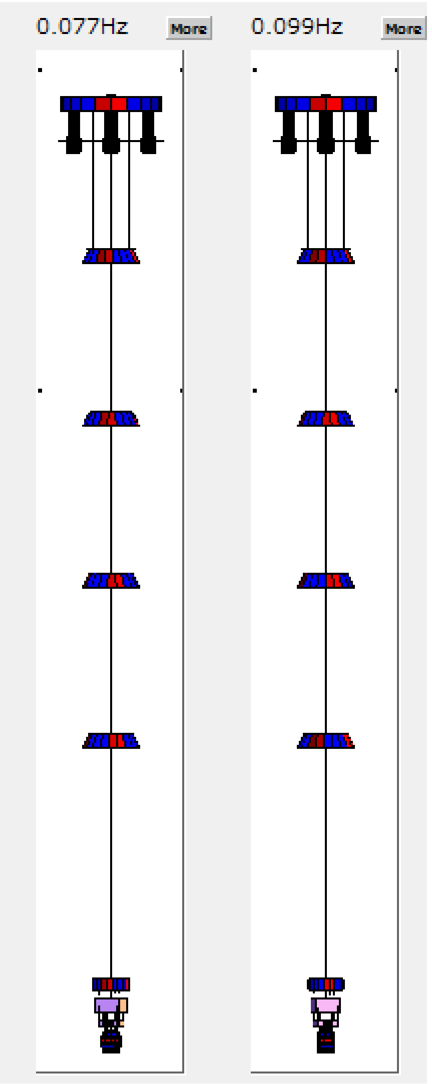
#1 #2 #3 #4 #5 #6 #7 #8

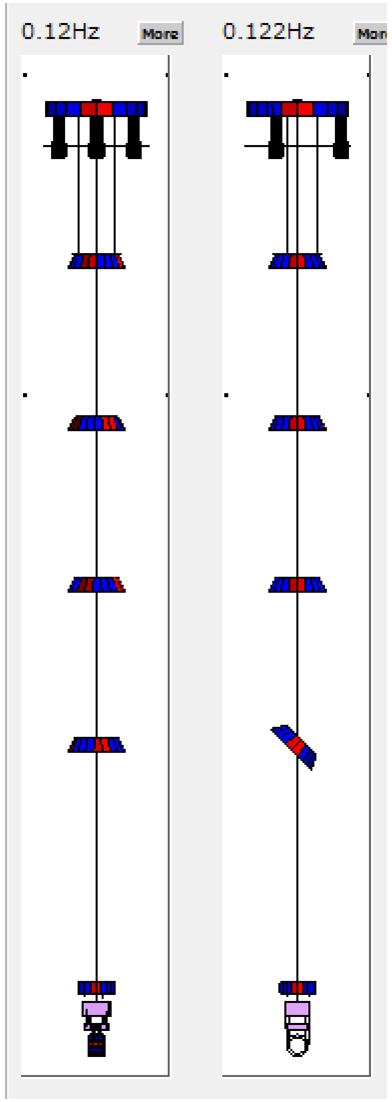


#3: 0.067 Hz

#4: 0.067 Hz

IP translational modes



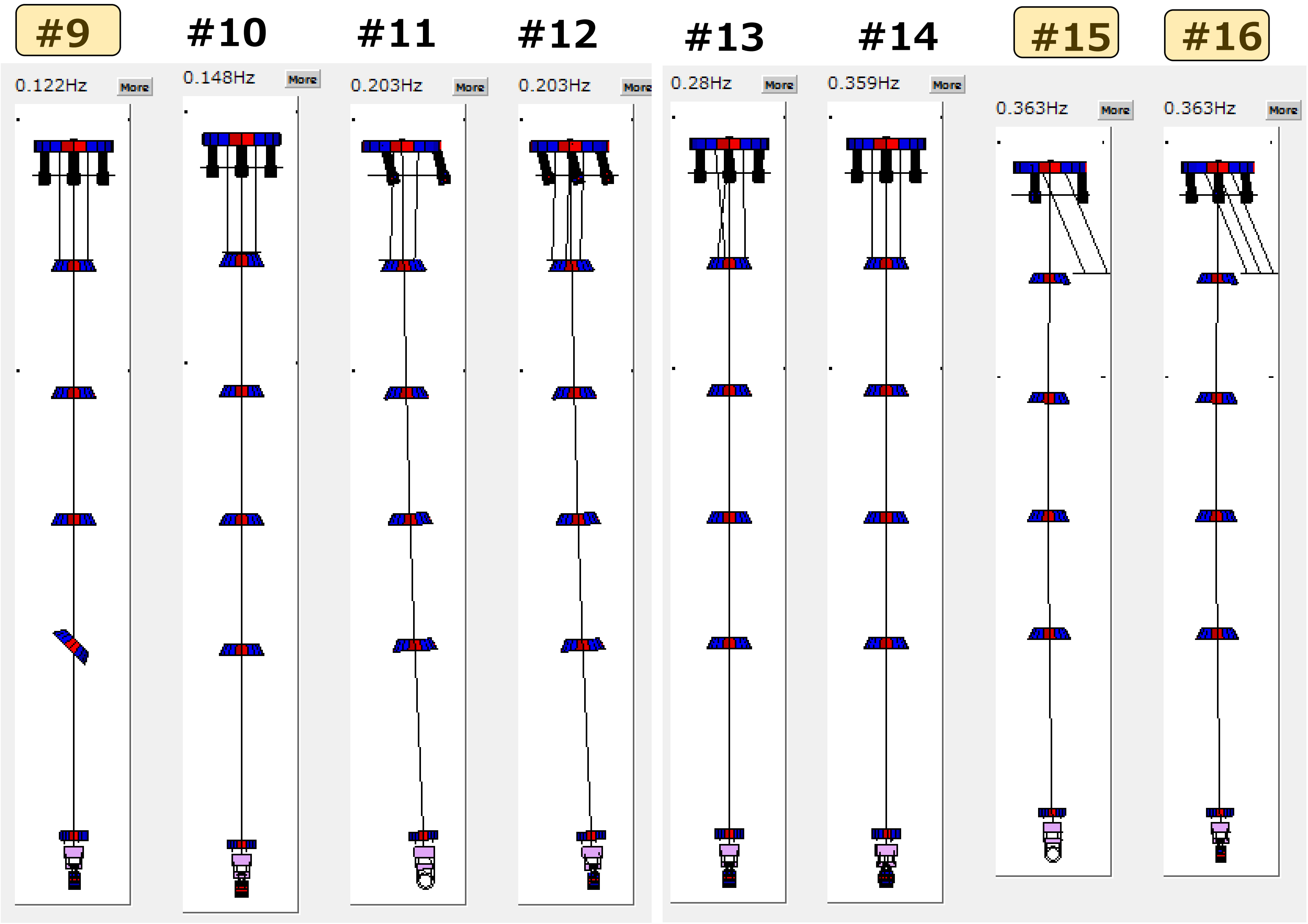


Type-A SAS,

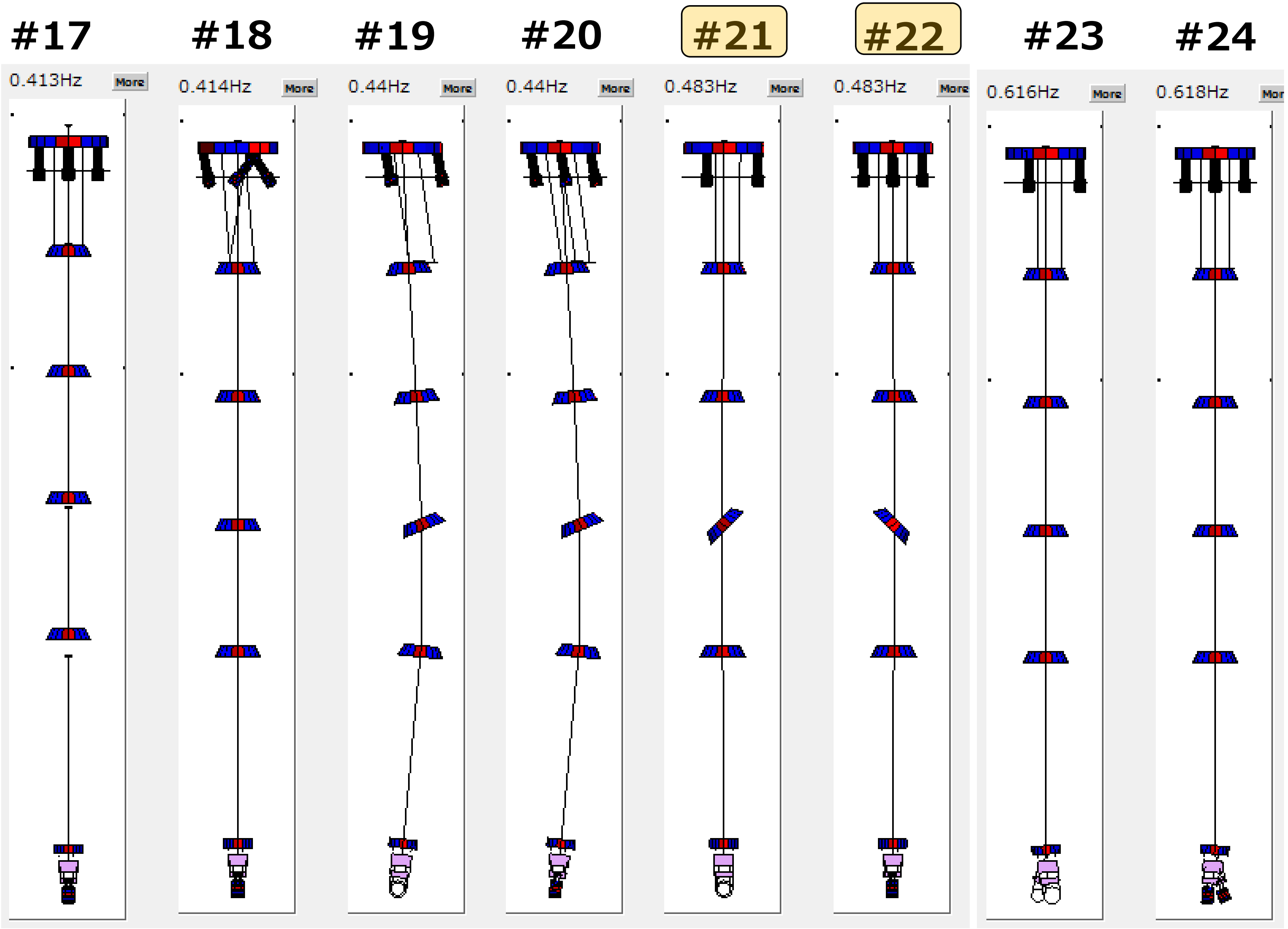
‘TyrpeA180429_20K’

Eigen mode: 75 modes

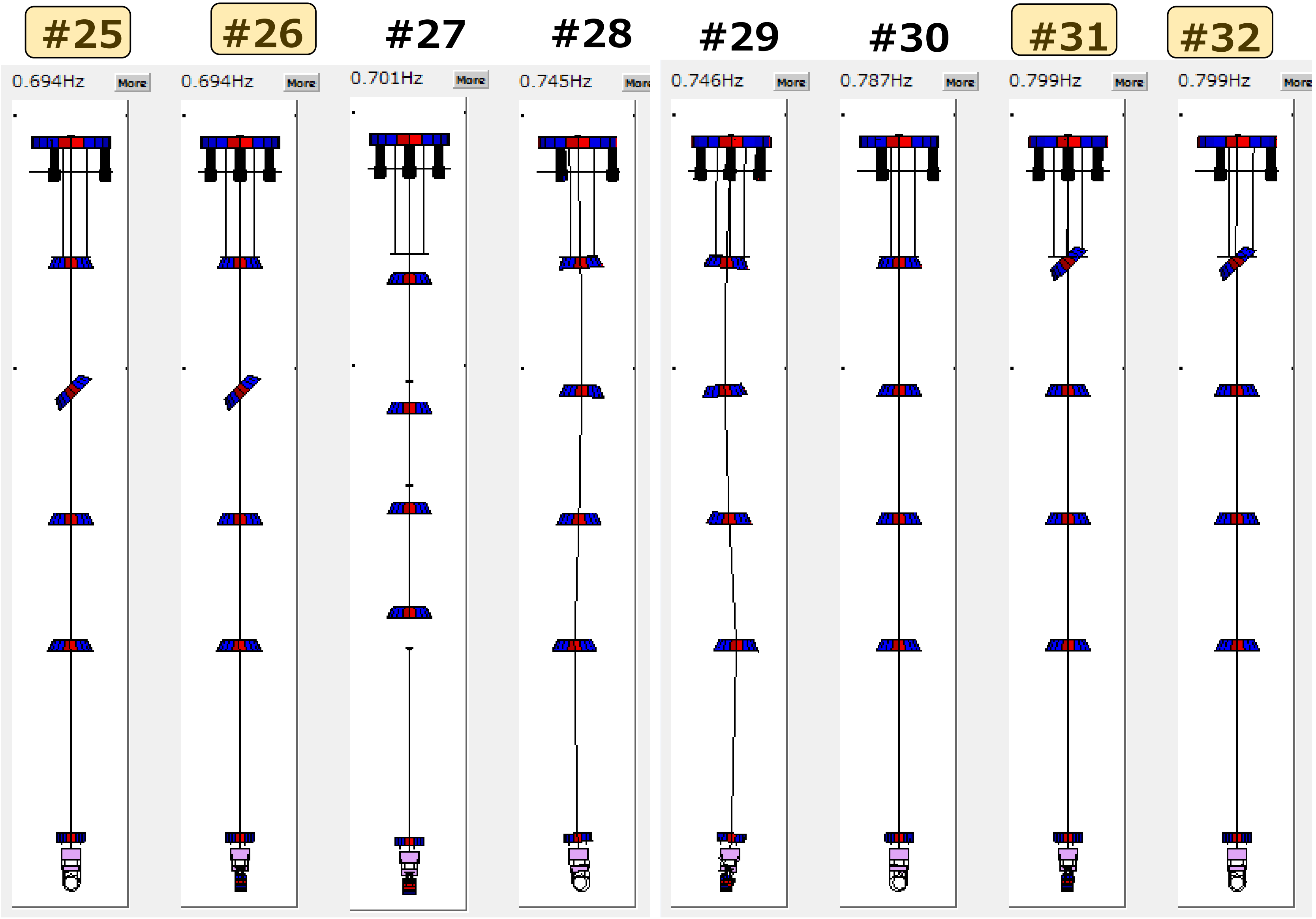
Less interest now



Less interest now



Less interest now



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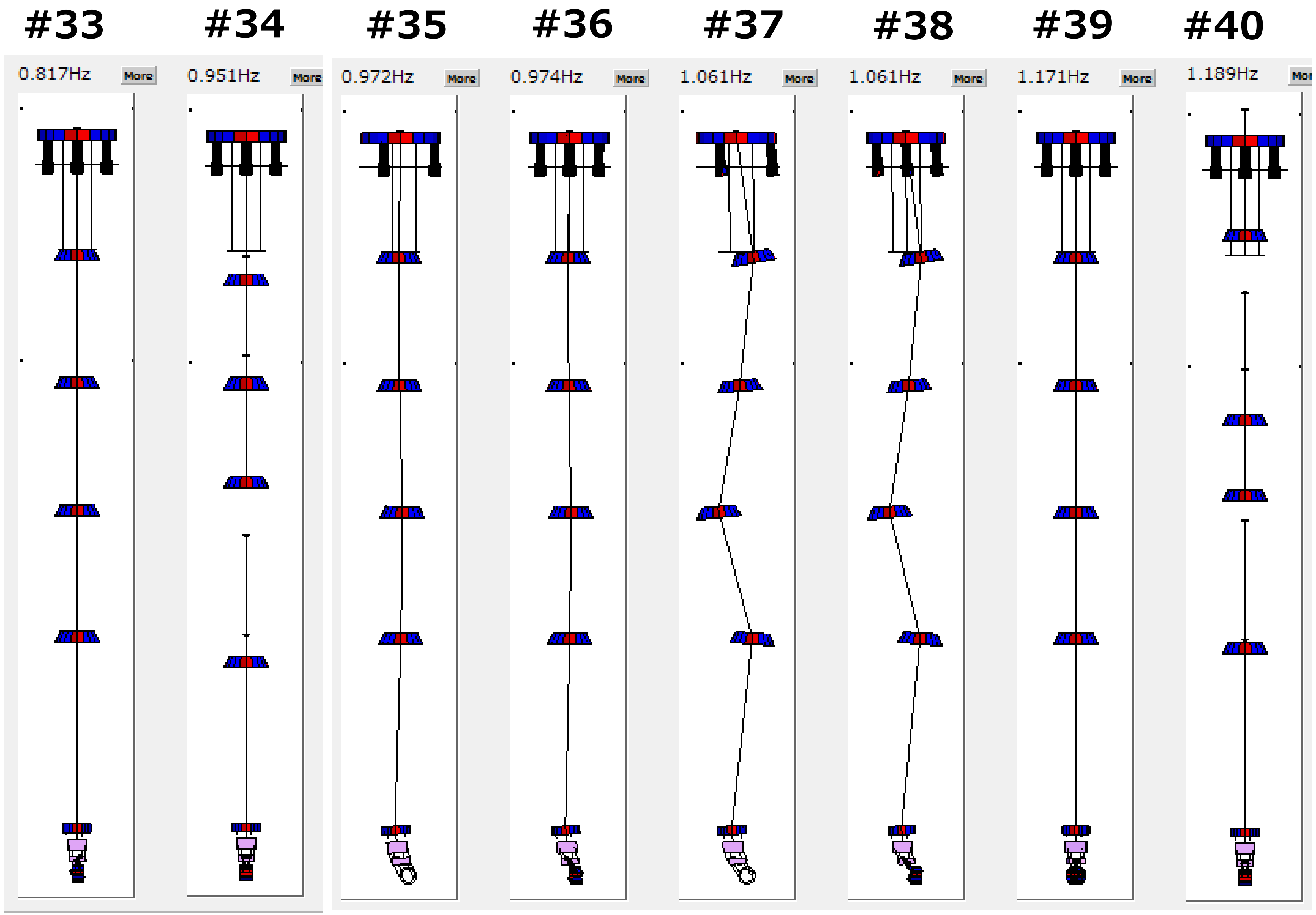

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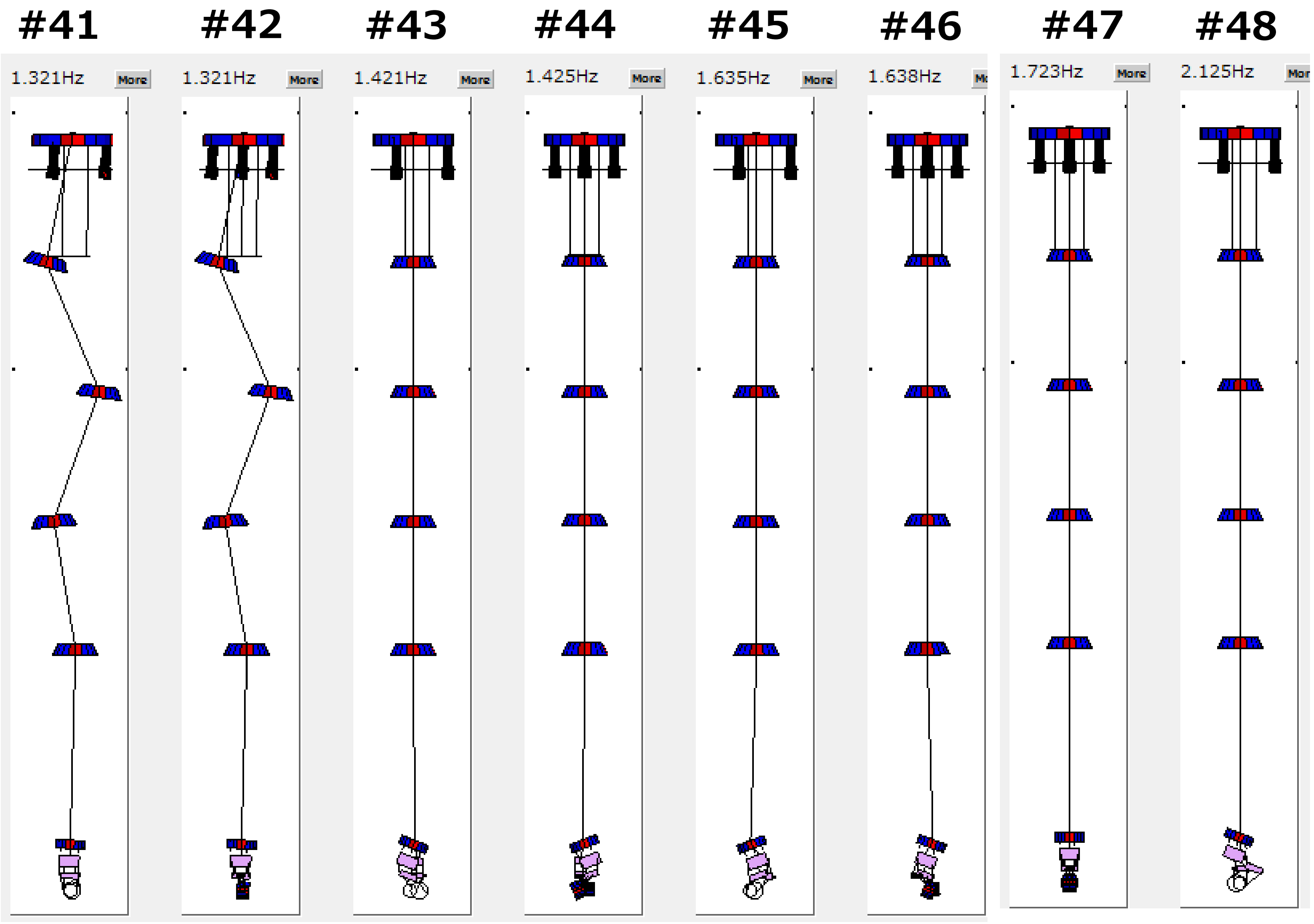

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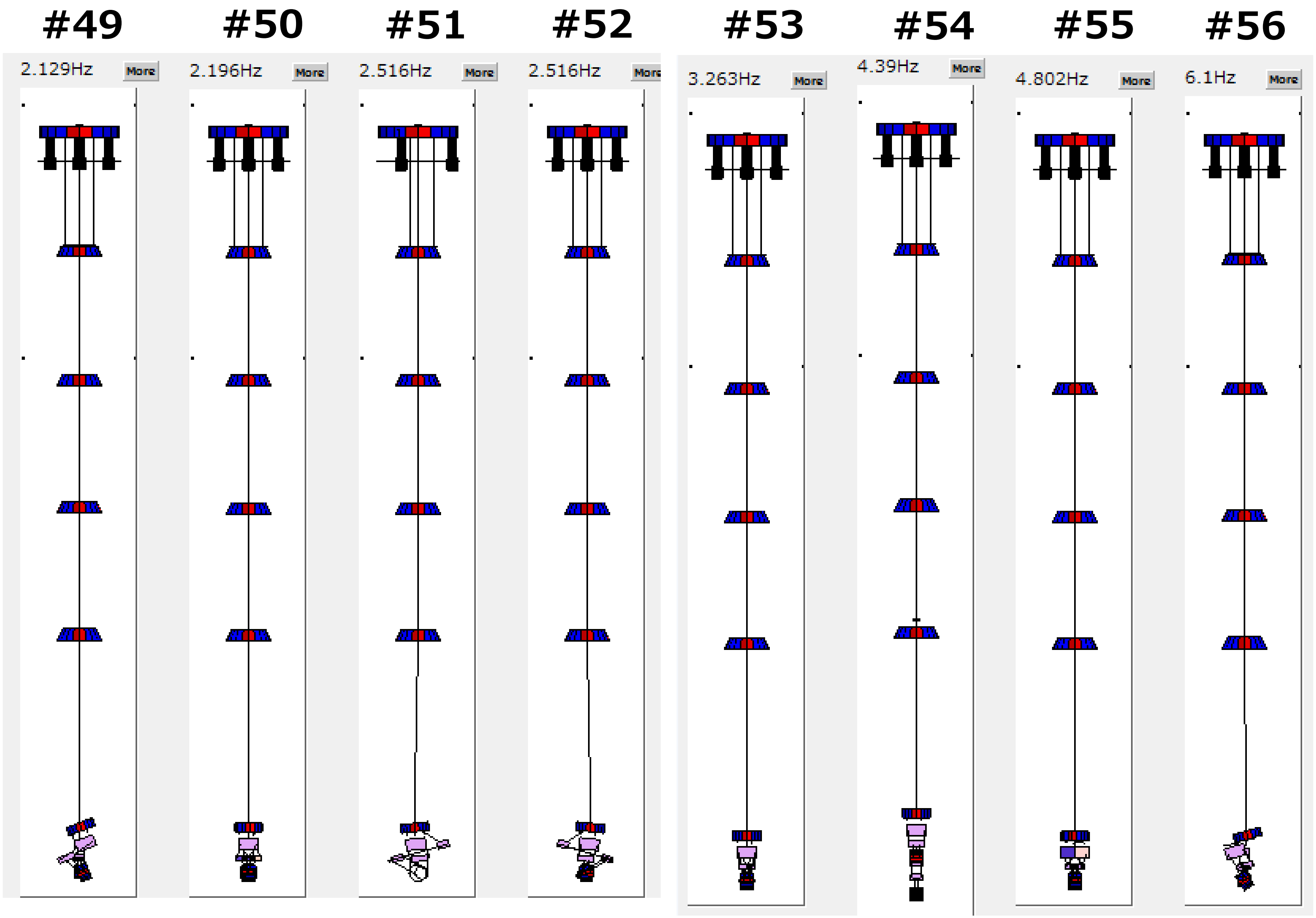

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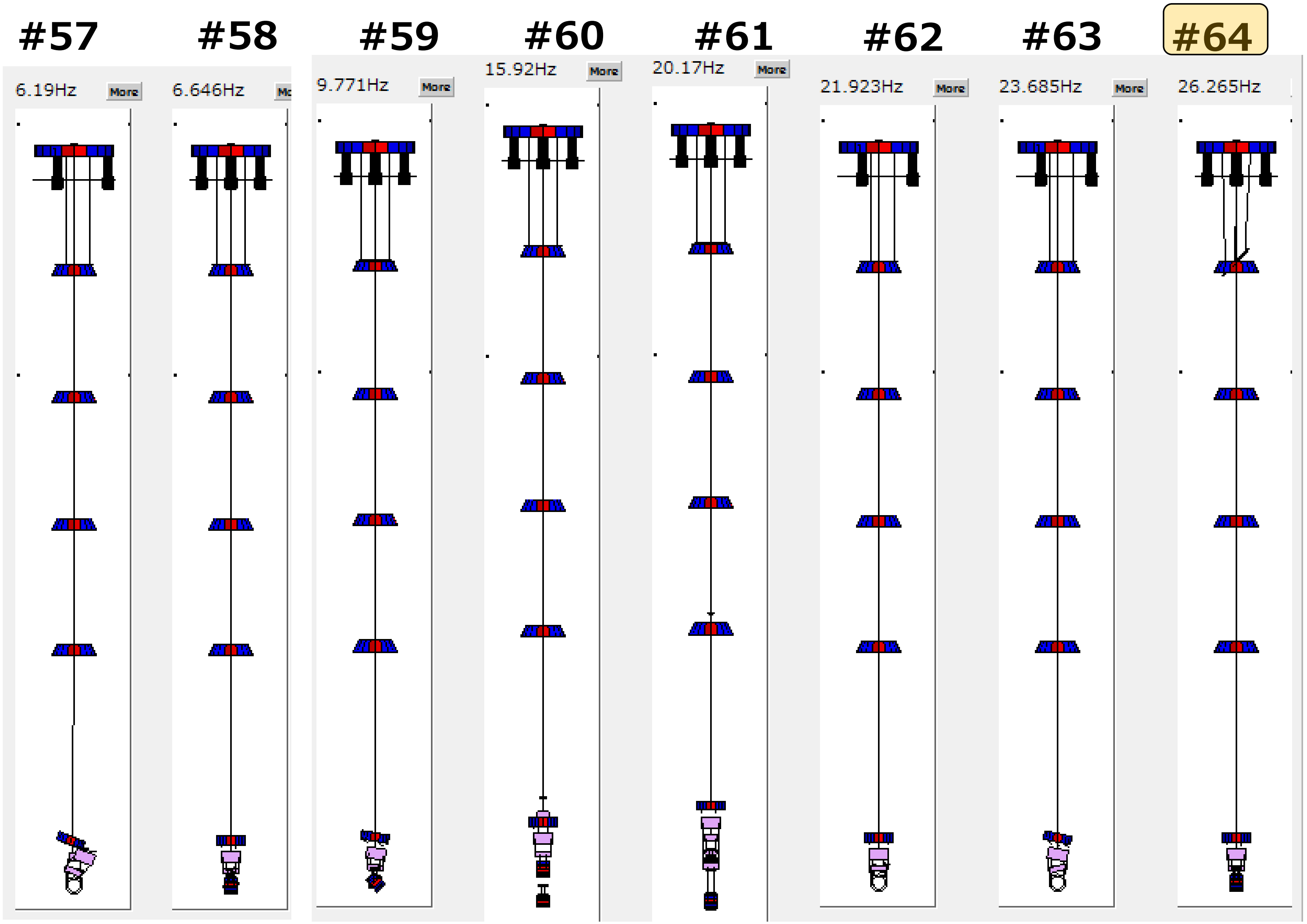

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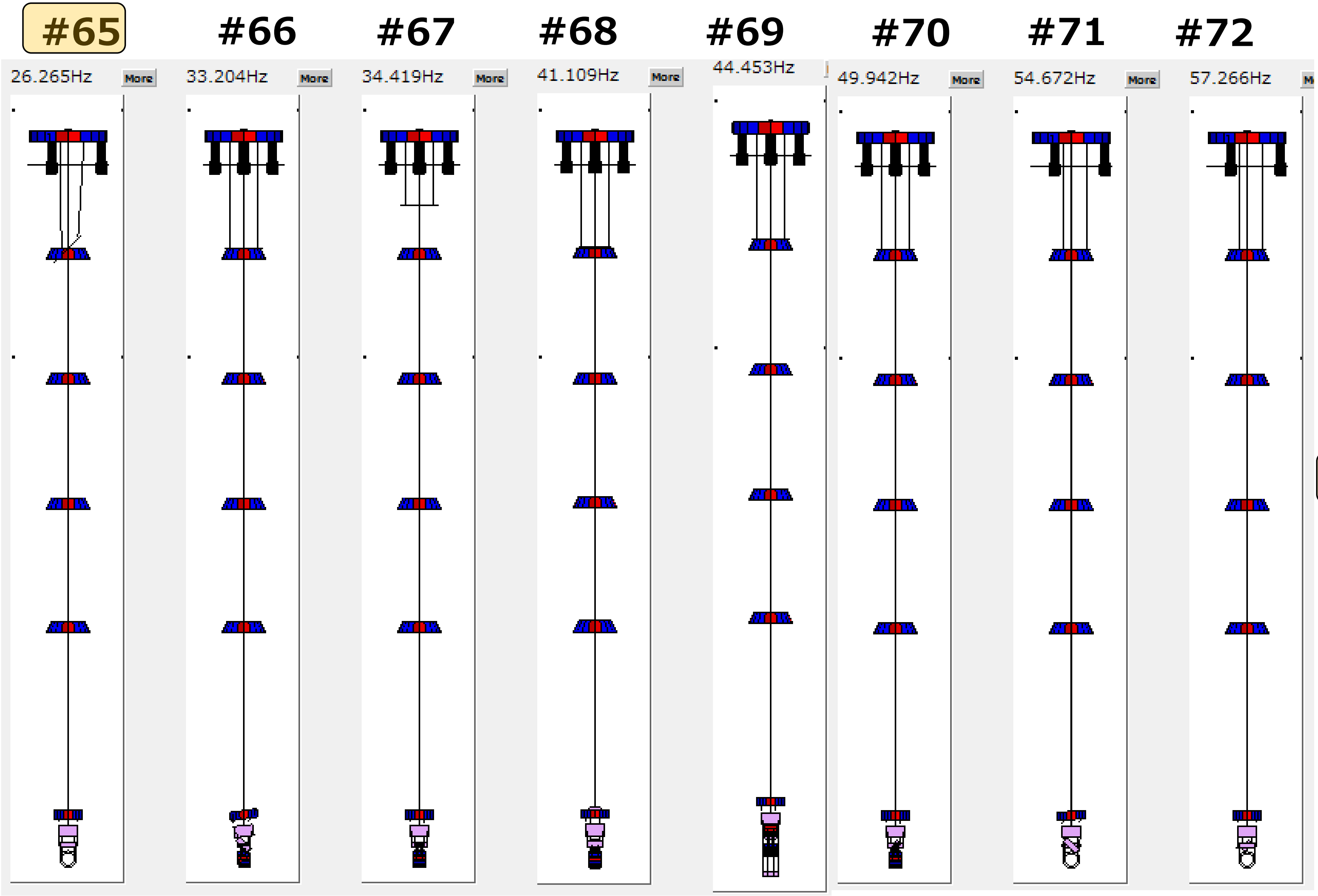

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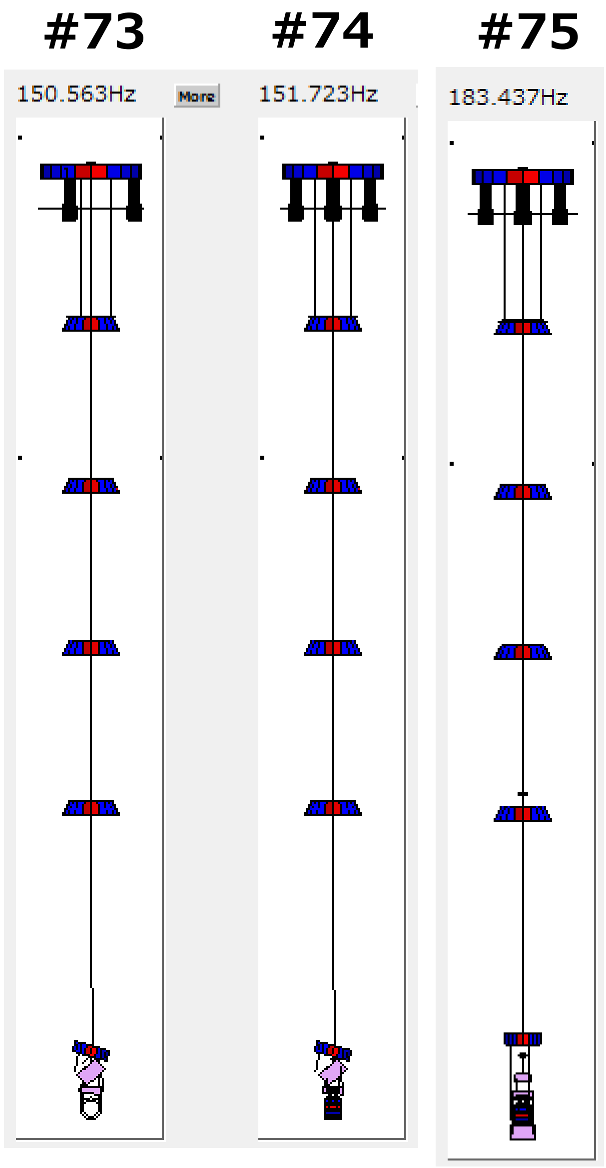

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