Active Vibration Isolation for TOBA – From the Past To the Future –

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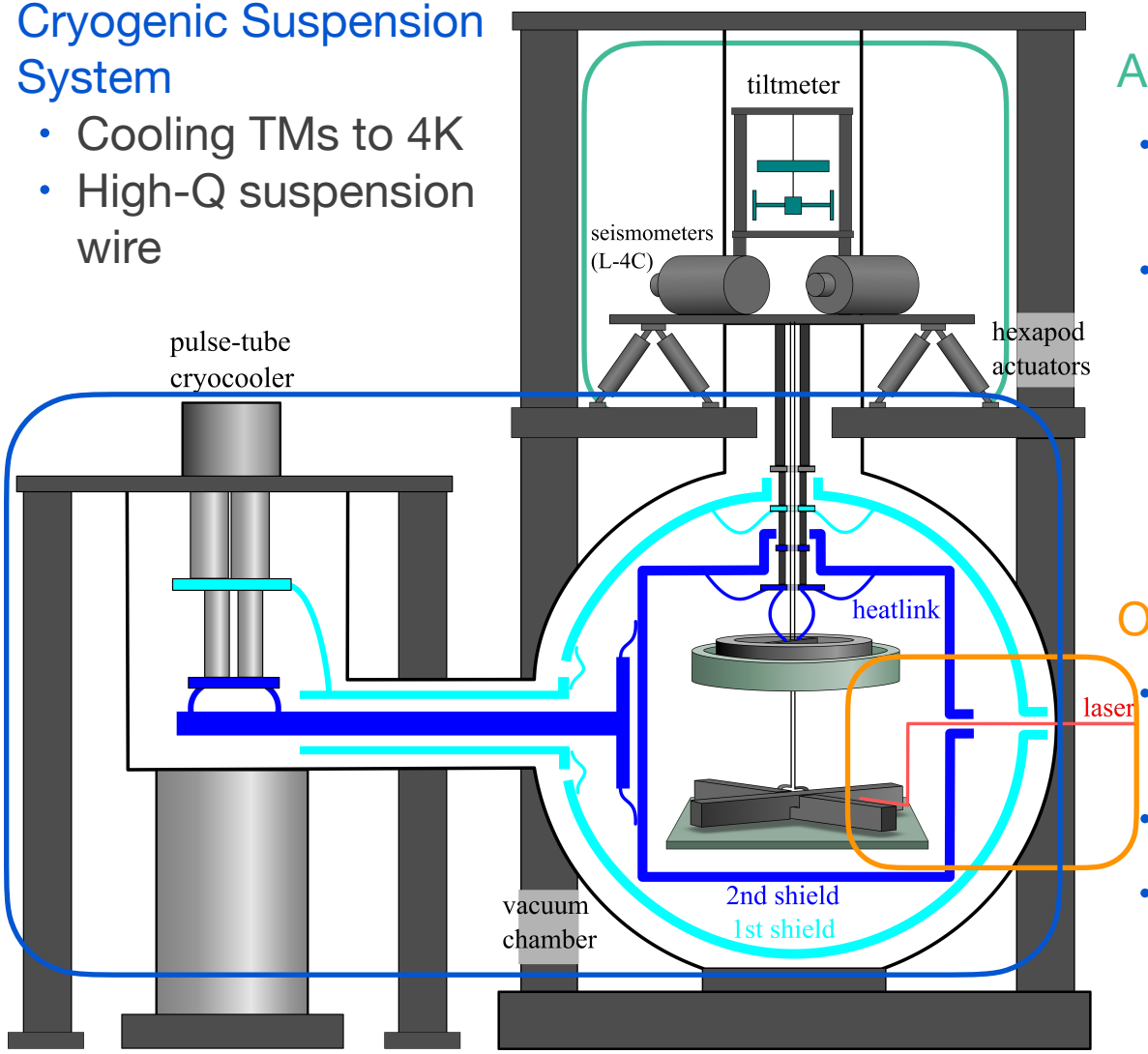
Ando Lab Seminar

2023/07/07

Overview of Phase-III TOBA

Cryogenic Suspension System

- Cooling TMs to 4K
- High-Q suspension wire



Active Vibration Isolation System

- Reduction of vibration at the suspension point
- Reduction of vibration induced cryocooler

Optical System

- Rotation measurement by intererometers
- Monolithic interferometer?
- Differential Fabry-Perot cavity?

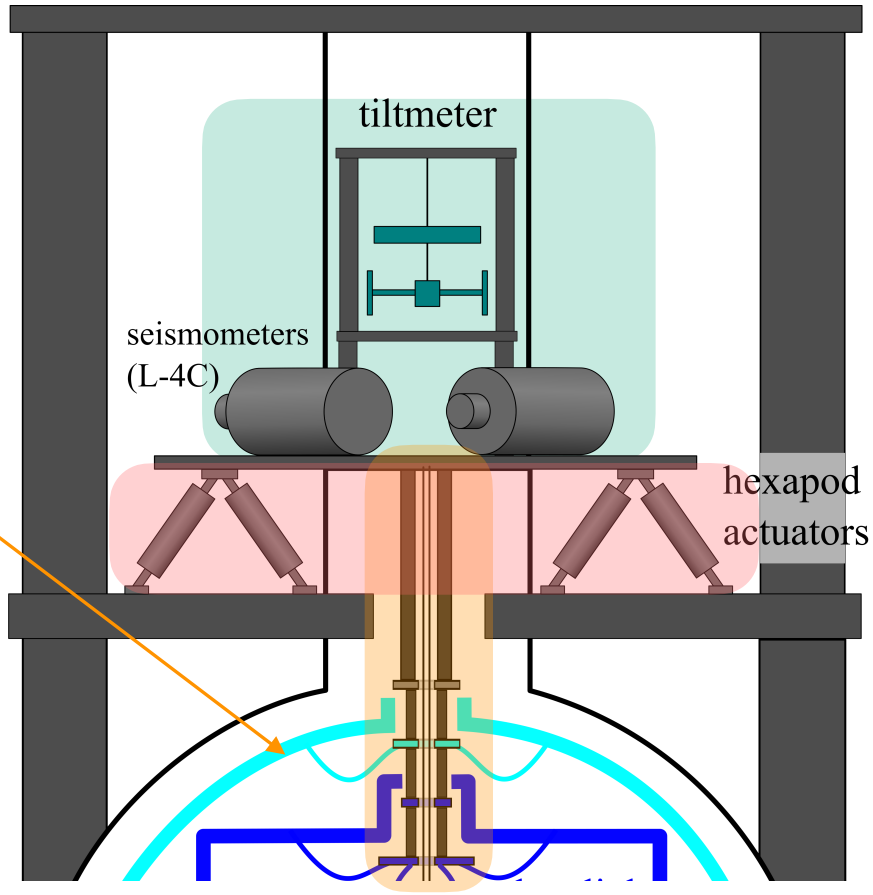
Basic Concept of AVIT

AVIT (Active Vibration Isolation Table):

- Reduction of seismic vibration
  - Coupling from horizontal vibration
    - 10^{-7} m/√Hz @ 0.1 Hz
  - Nonlinear coupling
    - 10^{-10} m/√Hz @ 1 Hz
- Reduction of vibration induced by cooler

Measure motion at the suspension point by seismometer & tilt meter

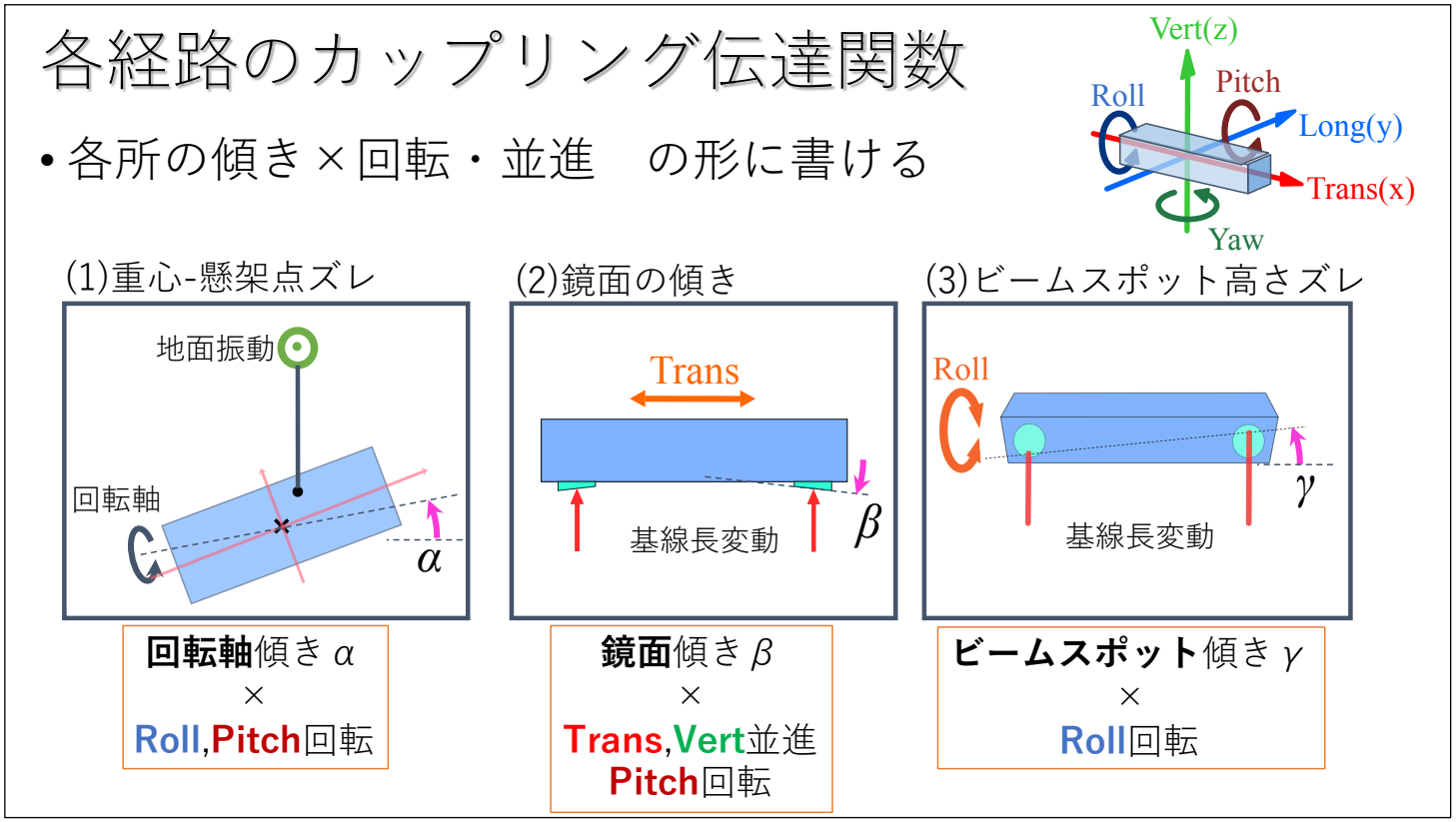
Feedback the signal to actuators to cancel out the motion



Seismic Vibration Isolation

Why is seismic vibration isolation necessary?

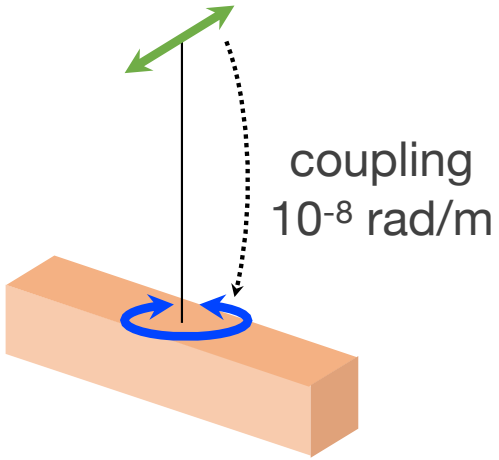
- Horizontal-yaw coupling noise



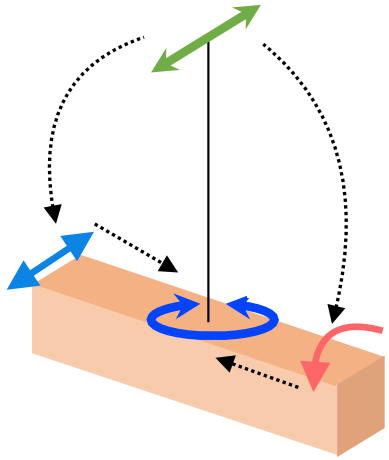
Classification of horizontal-yaw coupling (T. Shimoda, 2027)

Linear & Nonlinear Coupling

- Linear coupling: seismic translation x coupling factor
  - Coupling factor: required as **10^{-8} rad/m** for Phase-III TOBA
  - Need to tune tilt angle of TMs in this order



- Nonlinear coupling:
  cross term of
  resonant peak of pendulum mode and
  tilt motion induced by seismic translation
  - Need to reduce seismic vibration
    around resonant frequency
    of the pendulum modes (~ 1 Hz)



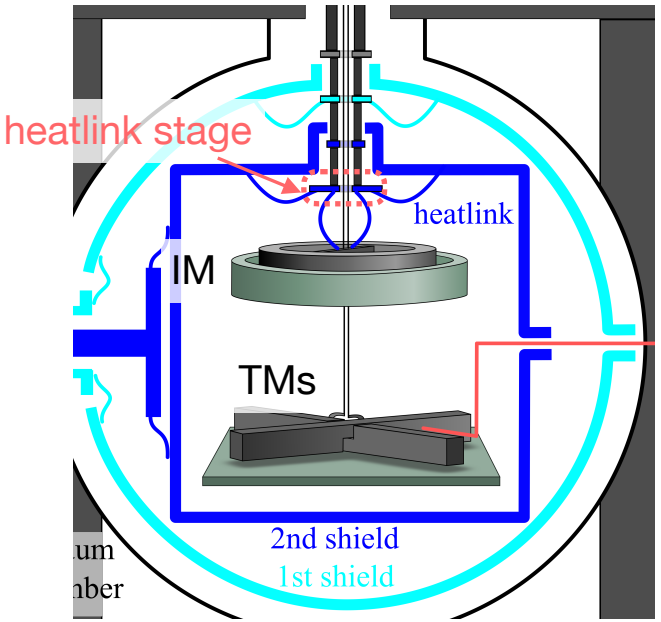
Vibration Isolation from Heatlink

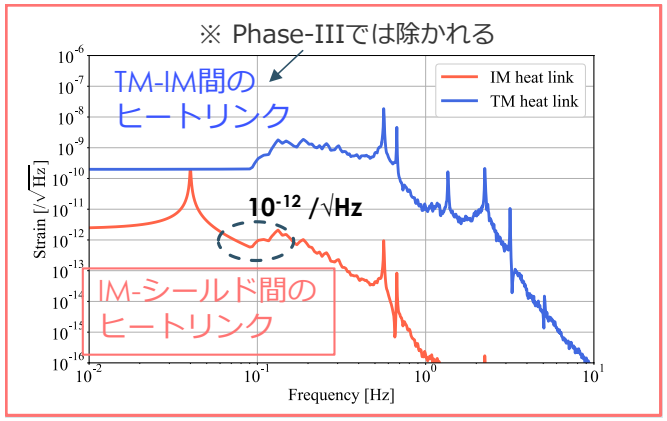
Vibration induced by heatlinks:

Vibration @ heatlink stage

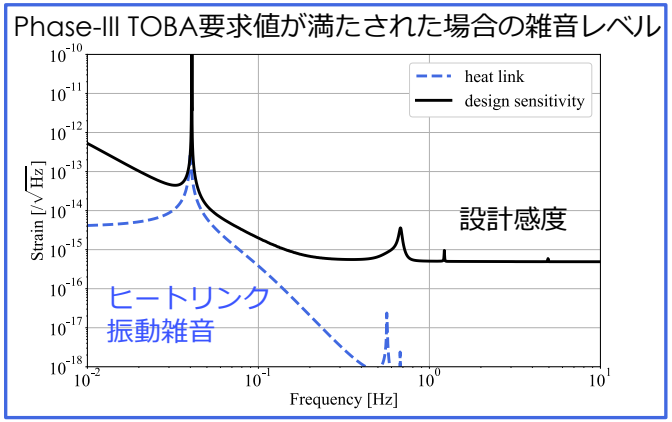
- Relative motion btw IM and heatlinks
- Torques on IM due to asymmetry (5%)
- Rotation of IM
- Common rotation of TMs

- No isolation: 10^{-6} m/√Hz translation
- With isolation: 10^{-7} m/√Hz translation



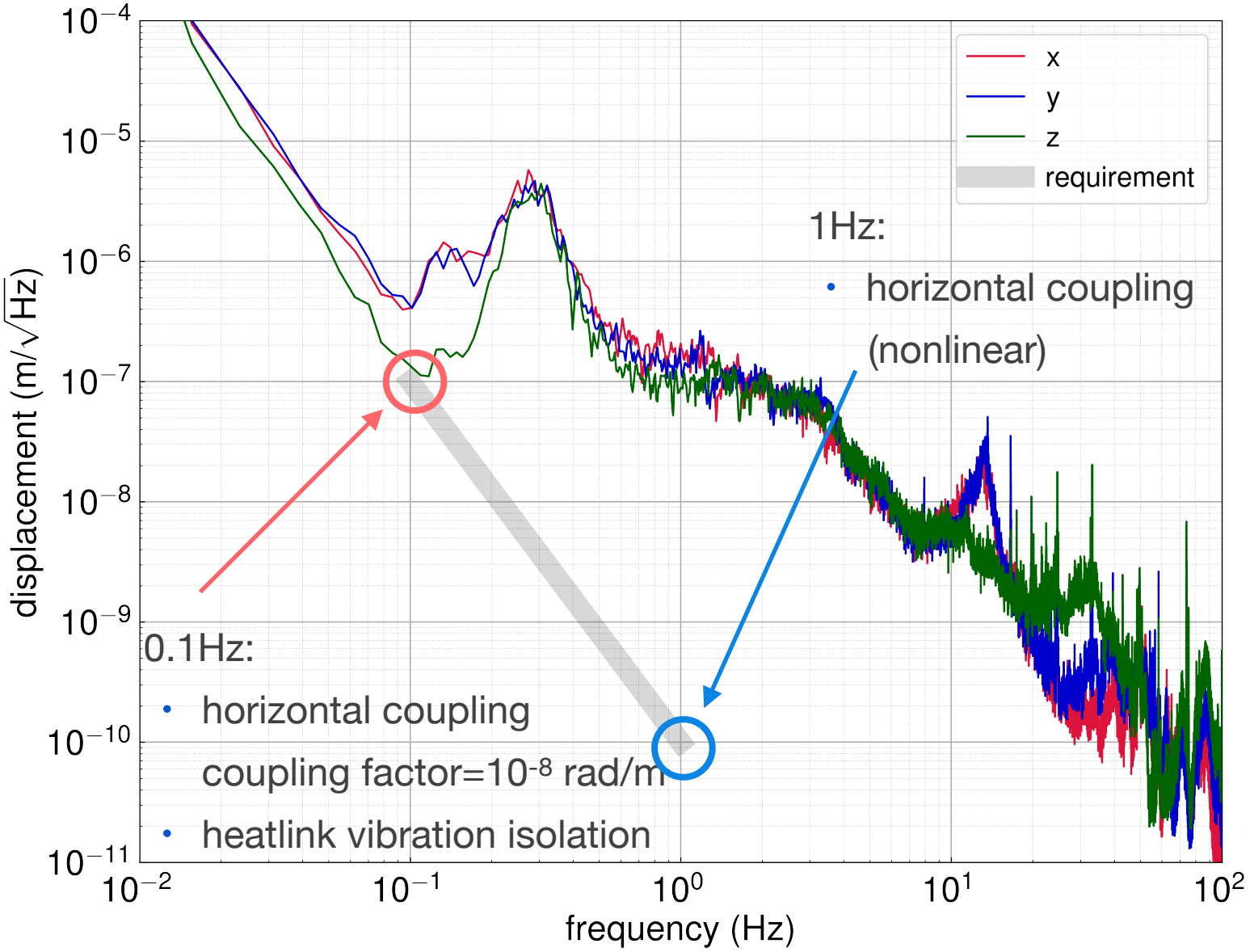


no isolation



with isolation

Requirements for AVIT

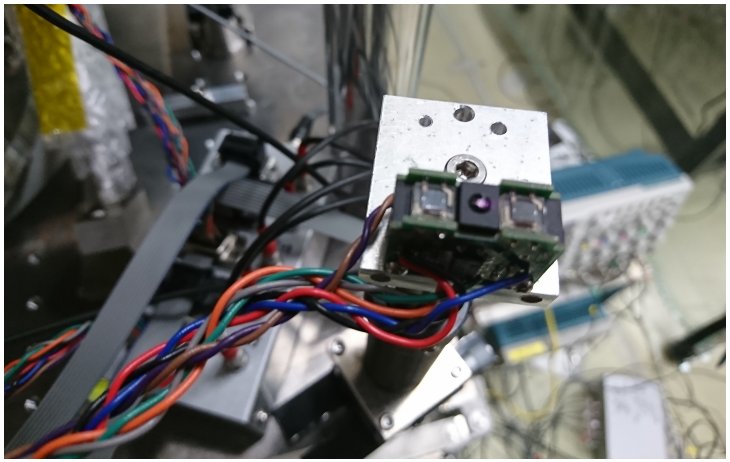


How to Control: Sensors

Sensors: 6 inertial sensors and 6 local sensors

- Inertial sensor
  - Measure displacement from the inertial frame
  - Now using geophone (a kind of speedometer)
  - Bad sensitivity below its resonance frequency (~ 1 Hz)

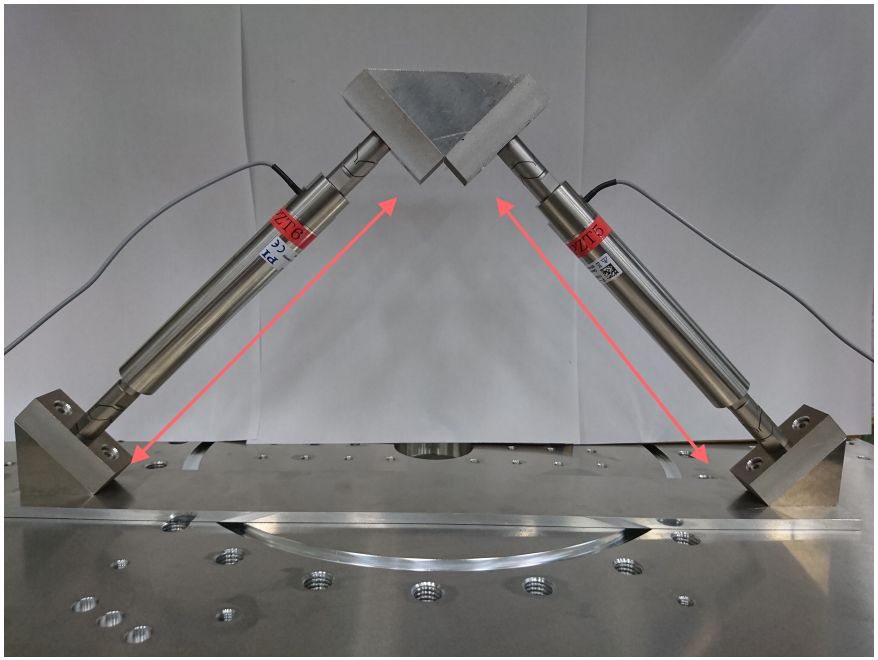
- Local sensor
  - Measure displacement between the support frame and AVIT
  - Reflective-type photosensor
  - Used in frequency where inertial sensor can’t see displamecent

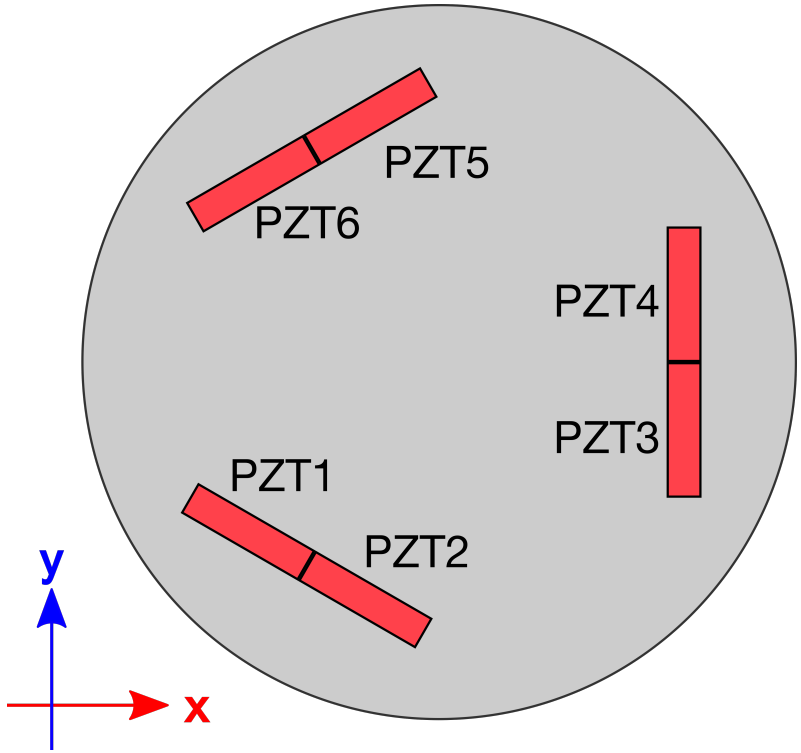


How to Control: Actuators

Actuators

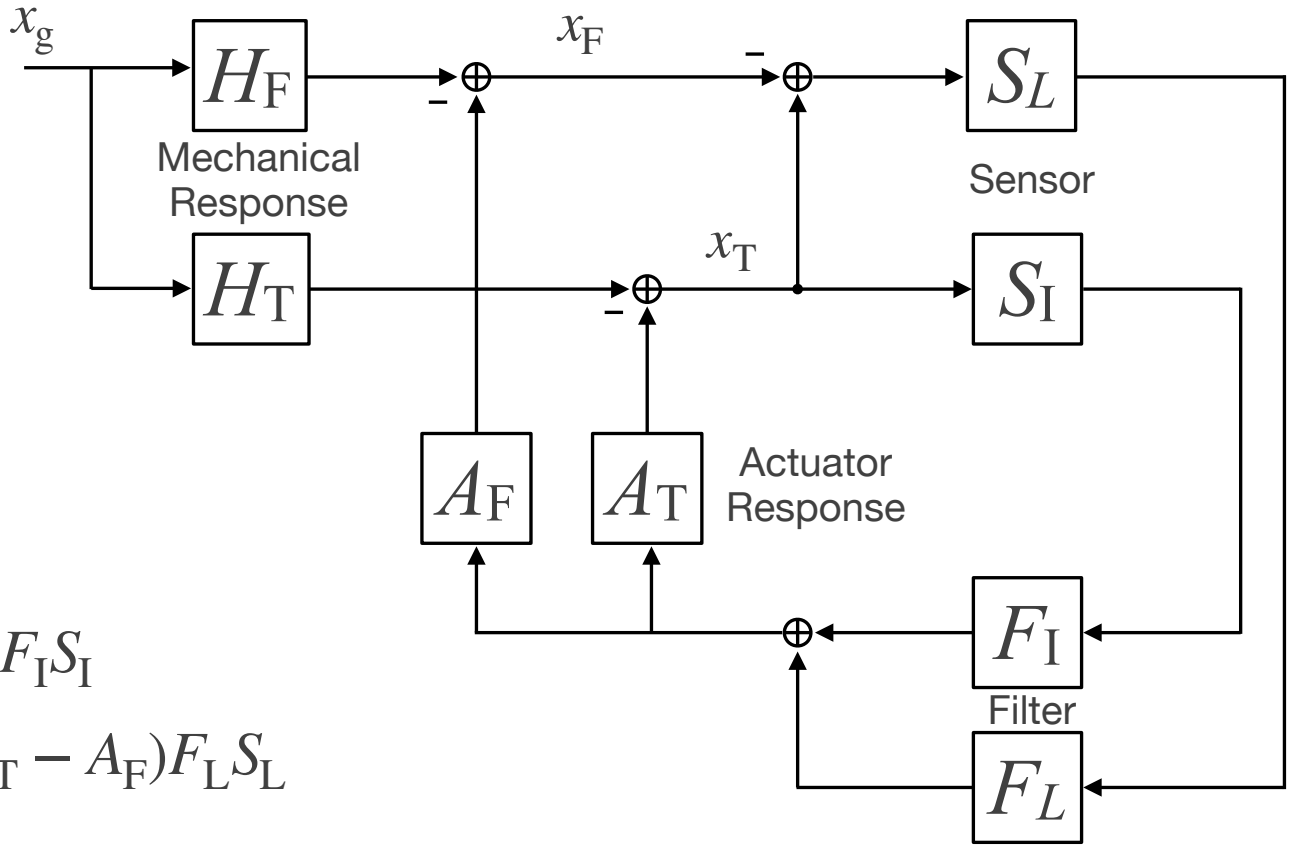
- Piezoelectric actuators (PZTs)
- Range of each PZTs: ~ 90 μm
- Range in translational DoF: 90 μm x √2 ~ 60 μm
- 6 PZTs in hexapod configuration





How to Control: Servo System

Diagram of the control loop



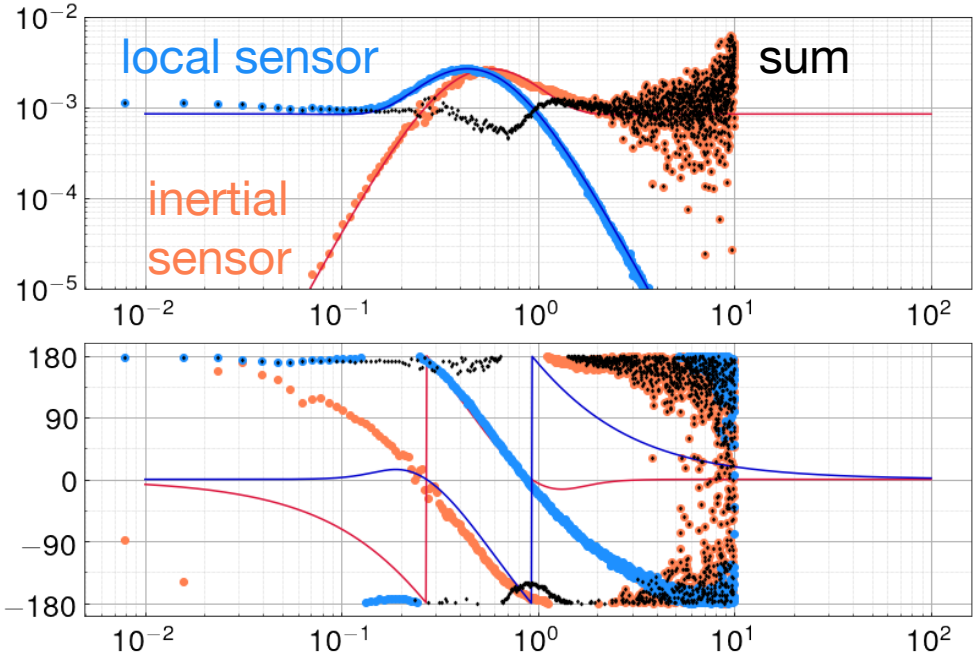
$$G_I := A_T F_I S_I$$

$$G_L := (A_T - A_F) F_L S_L$$

Isolation ratio: $\dfrac{x_T}{x_g} \simeq \dfrac{1 + G_L}{1 + G_I + G_L}$ ($H_F \simeq H_T$のとき)

Filter Design

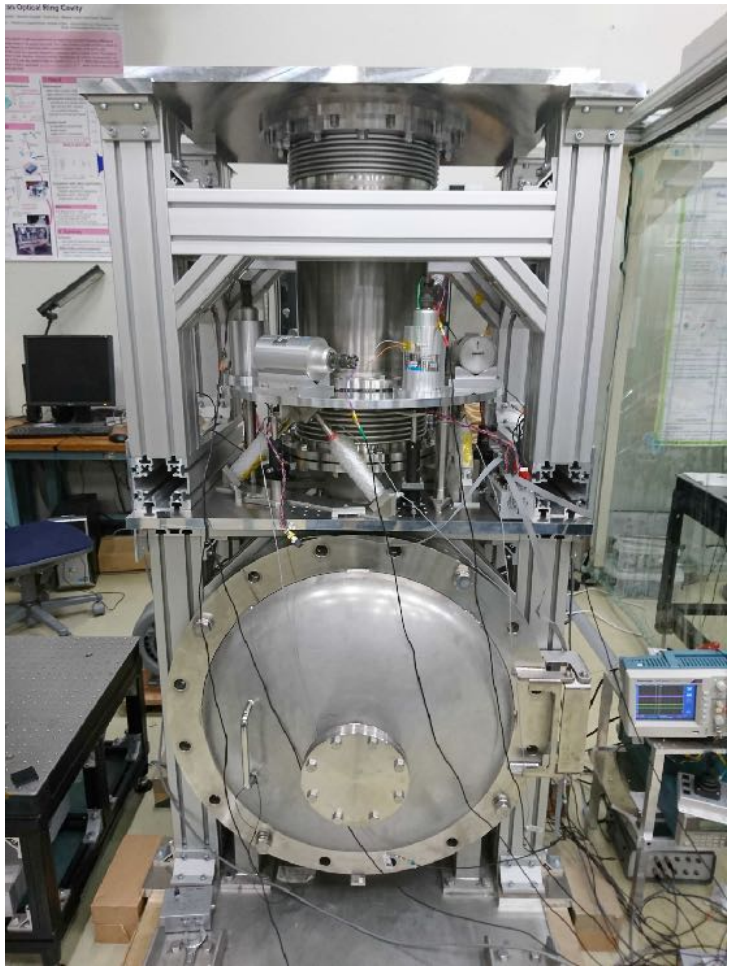
- Overall filter: blending filter + servo filter
- Blending filter
  - Mix an inertial sensor signal and a local sensor signal
  - Designed to be unity gain and no phase change

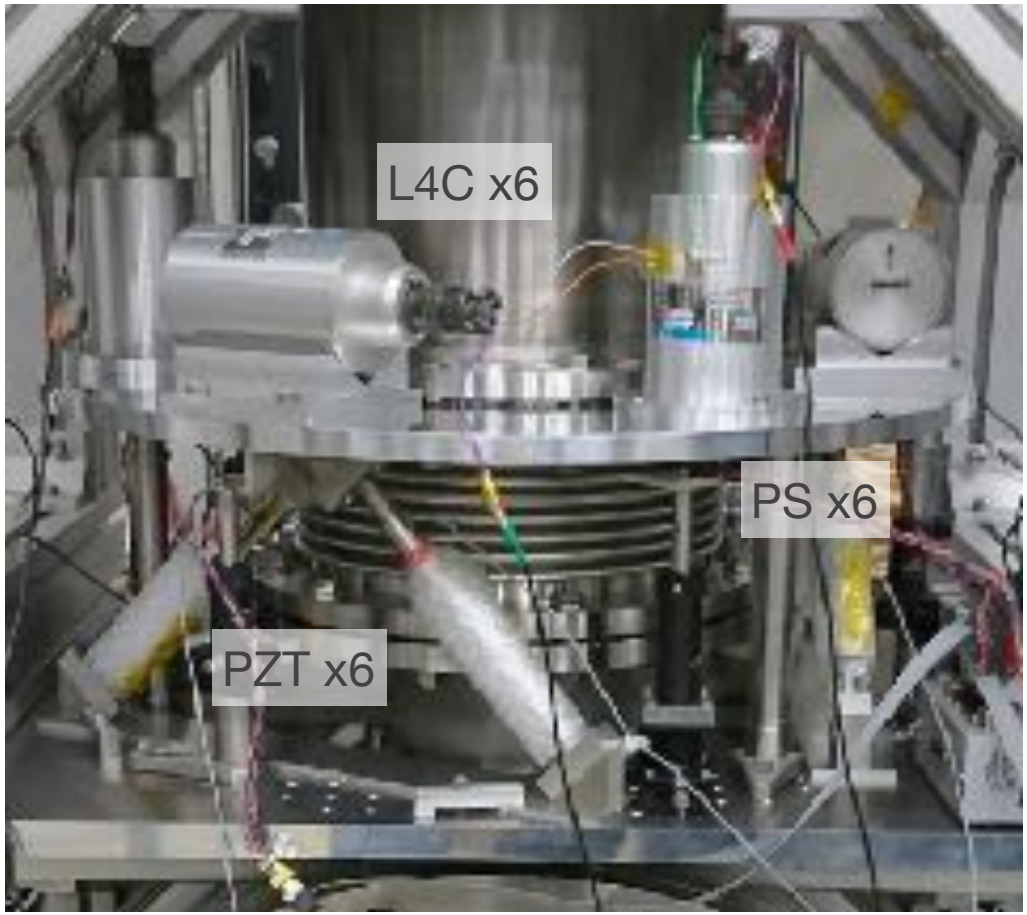


- Servo filter
  - Lowpass filter @ 0.1 Hz + DC gain Boost (2 Hz pole & 30 Hz zero)

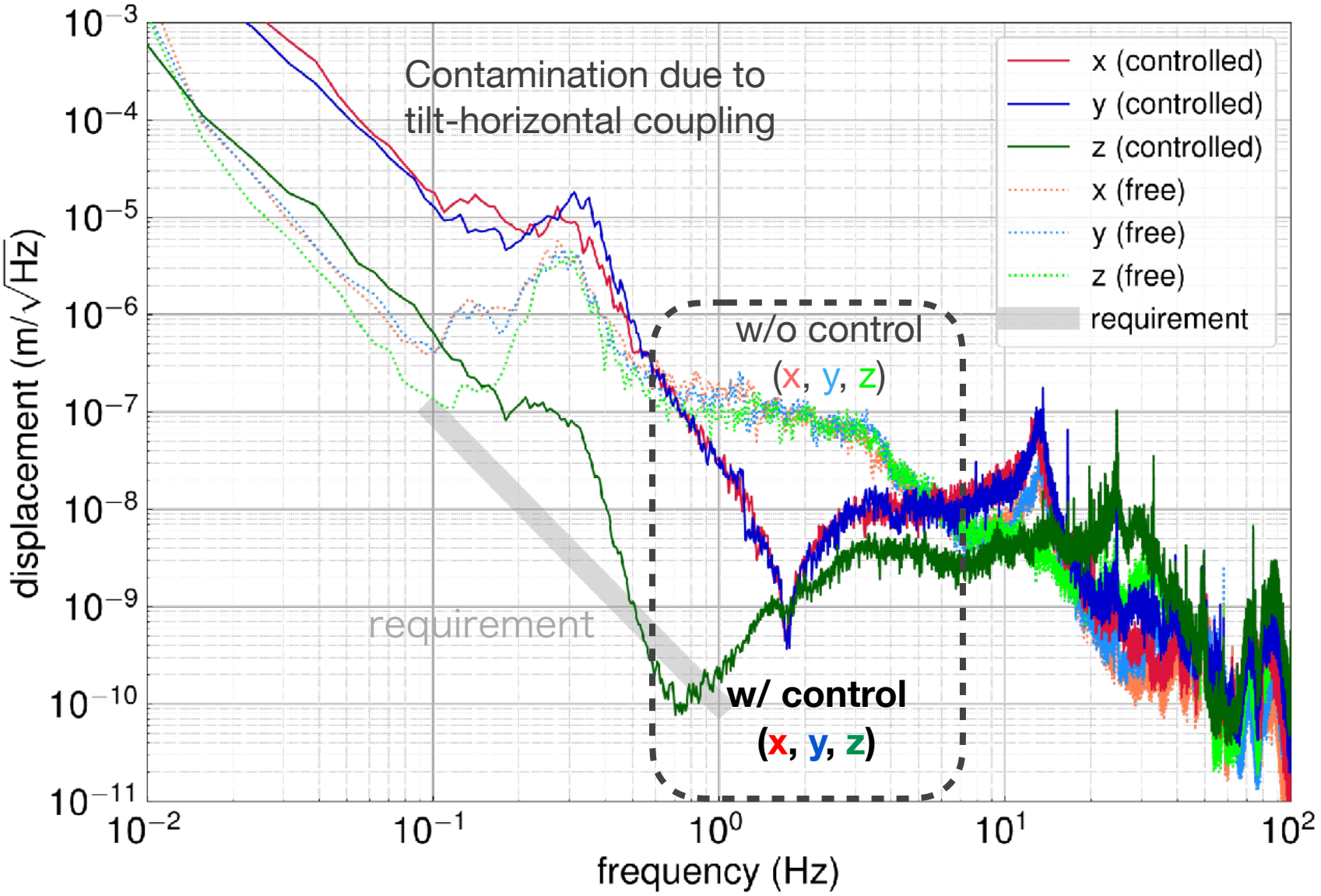
Current Performance

- Done on 2019/05/30
- Different vacuum chamber , no suspensions, no cryostat,





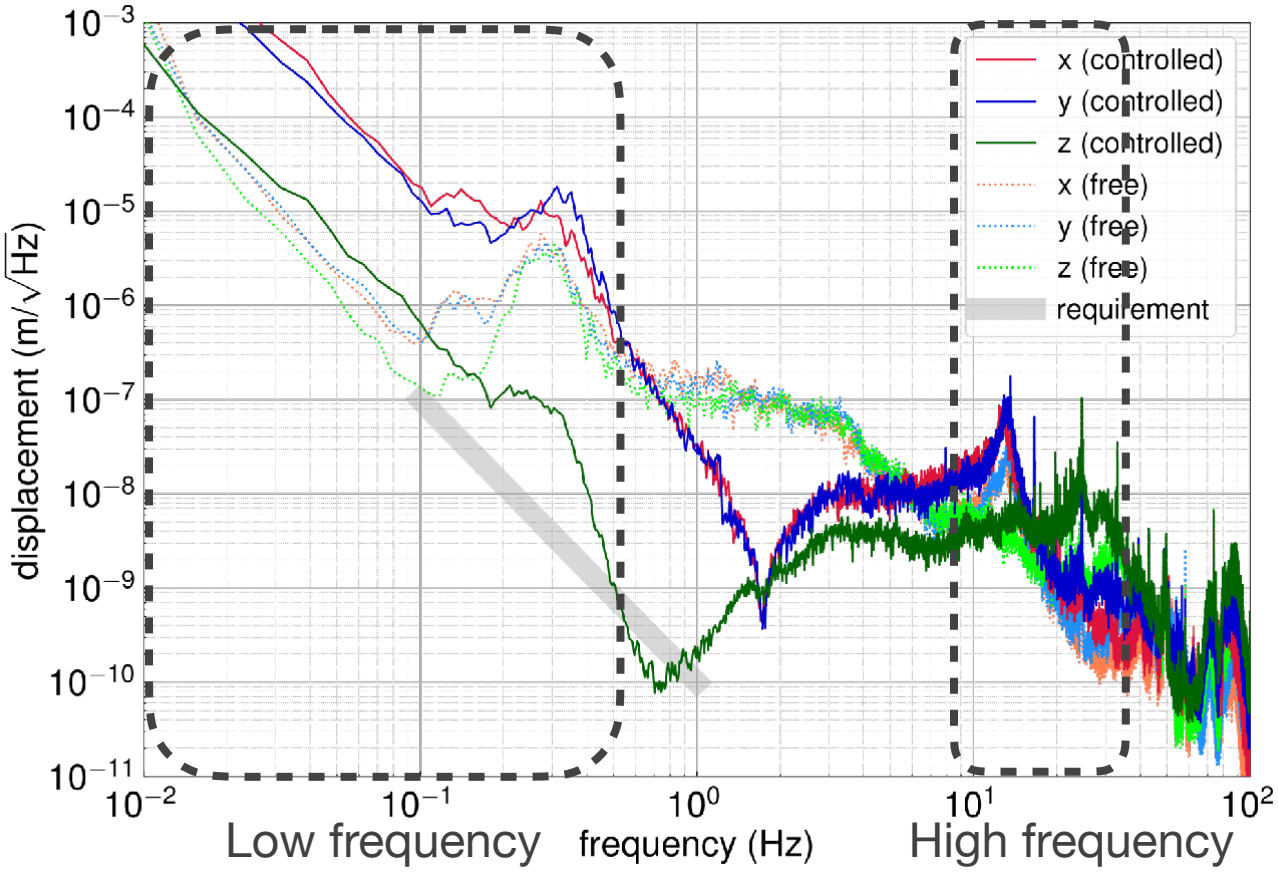
Current Performance of AVIT



Problems

Mainly two problems

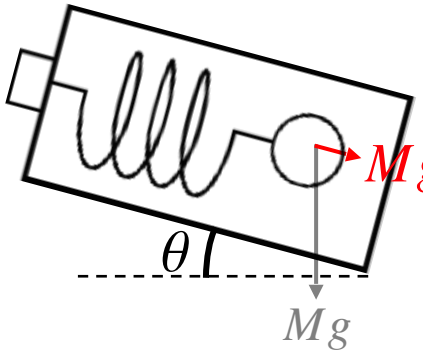
- Low frequency (< 0.7 Hz): Tilt-horizontal coupling (x, y)
- High frequency (>10 Hz): Mechanical resonance modes



Tilt-Horizontal Coupling

Tilt-horizontal coupling

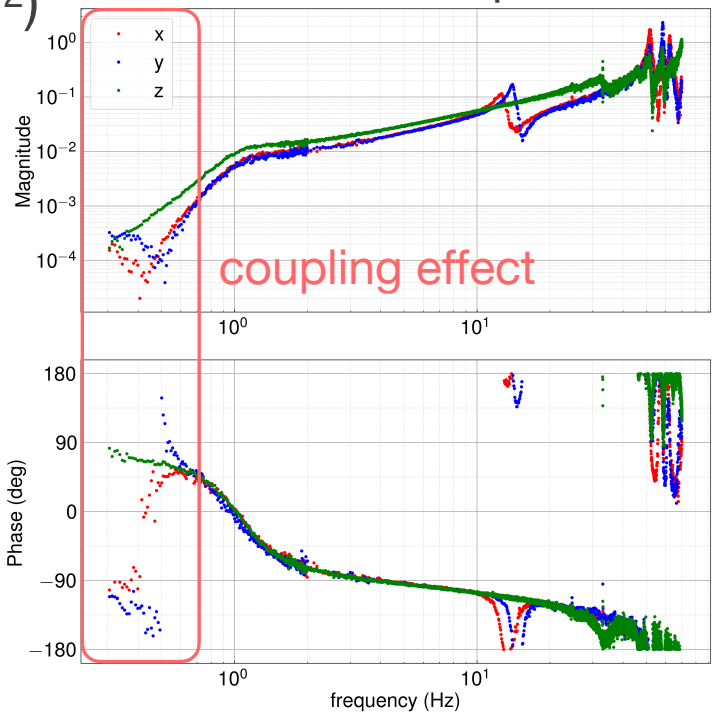
- Inertial sensor cannot distinguish tilt and translation motion
- Actuated in x (y)
  - Simultaneously moves in pit/roll
- Coupling gets larger in low frequency ($\propto f^{-2}$)
- Makes feedback loop unstable



$$M\ddot{x} = Mg\theta$$

$$\tilde{x} = -\frac{g}{\omega^2}\tilde{\theta}$$

Actuator Response

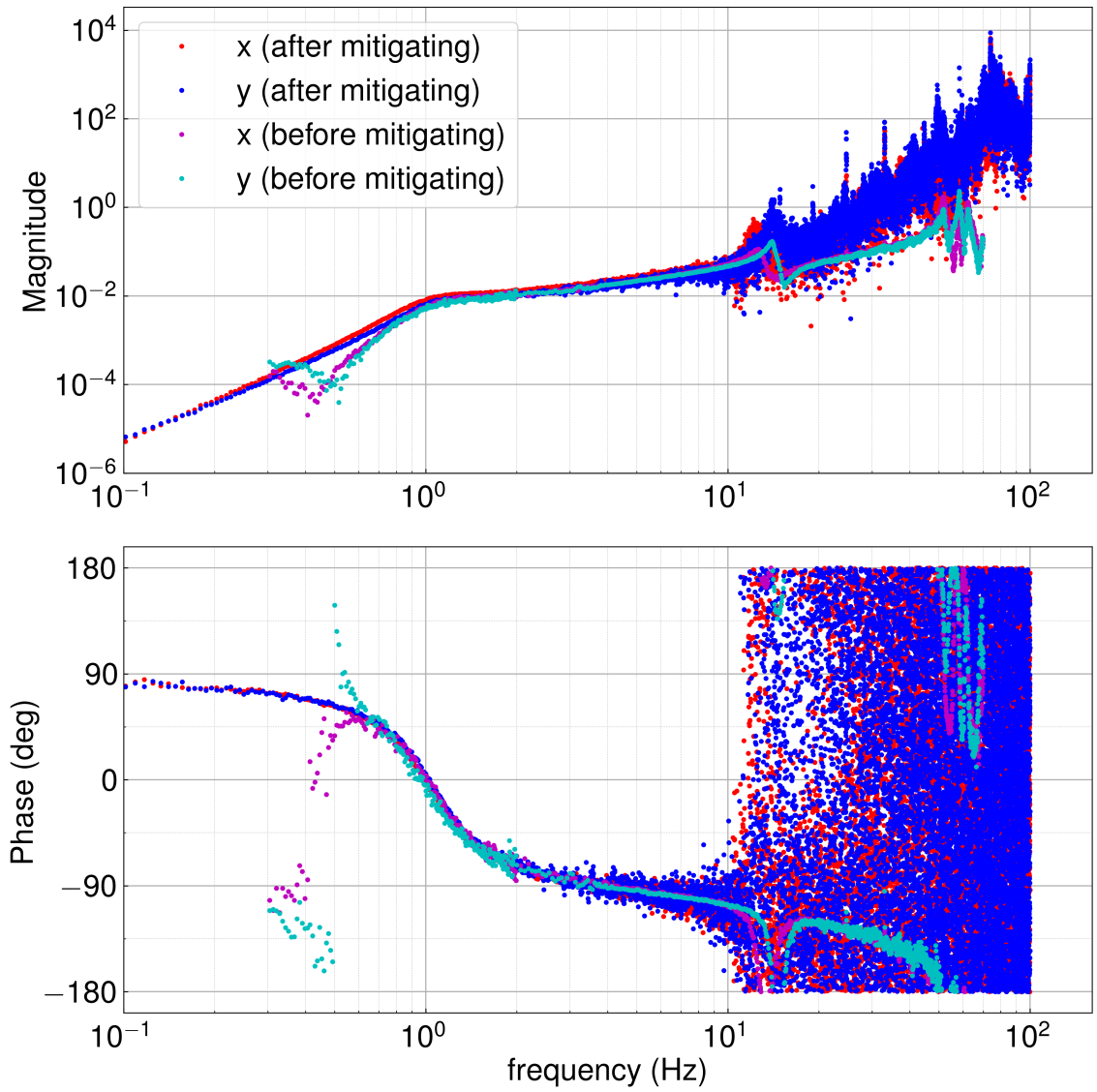


How to mitigate it?

- Feedforward (diagonalization)
  - Mix actuator DoF
- Active control
  - Measure tilt independently
  - Local sensor / Tiltmeter

Mitigation of Tilt Horizontal Coupling

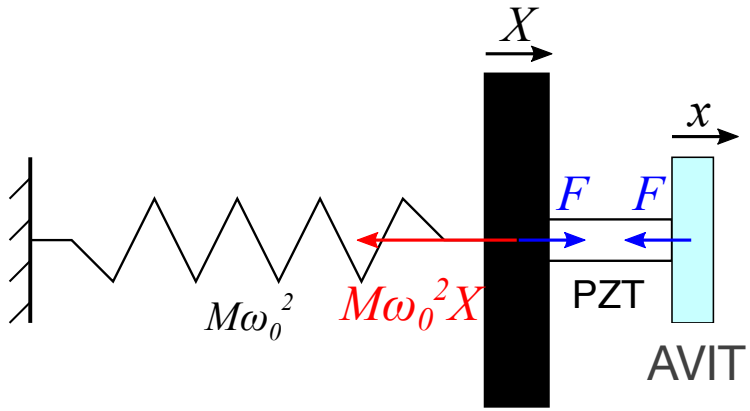
- Mix translation and tilt motion
- Finally coupling was reduced by < 10 %



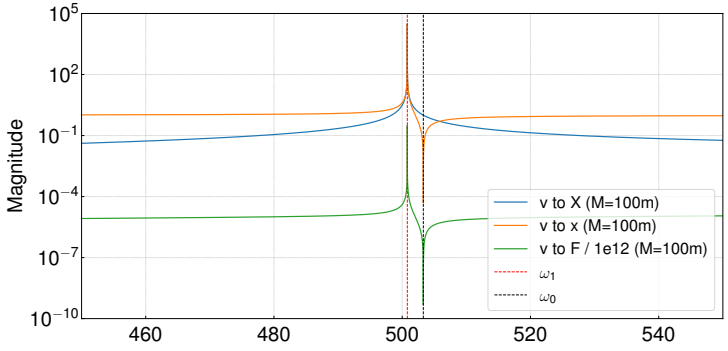
Mechanical Resonance Modes

Parasitic resonance in actuator response

- Mechanical resonance modes of the supporting frame
  - Actuator kicks these modes
  - Resonance-dip pair appear

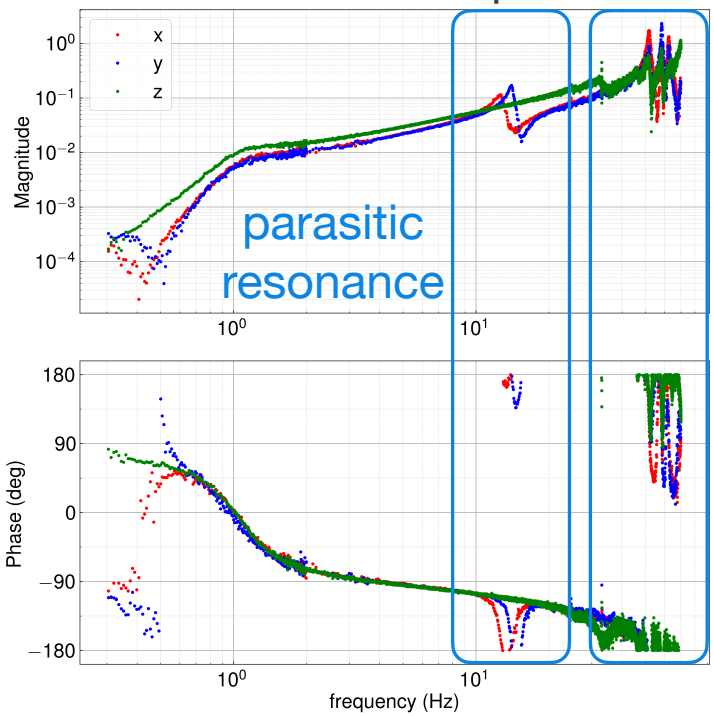


supporting frame



modeling

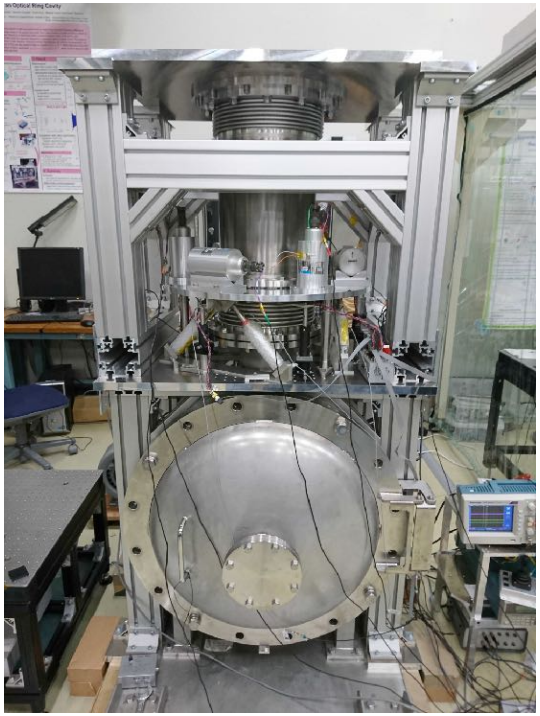
Actuator Response



Evolution of Frames

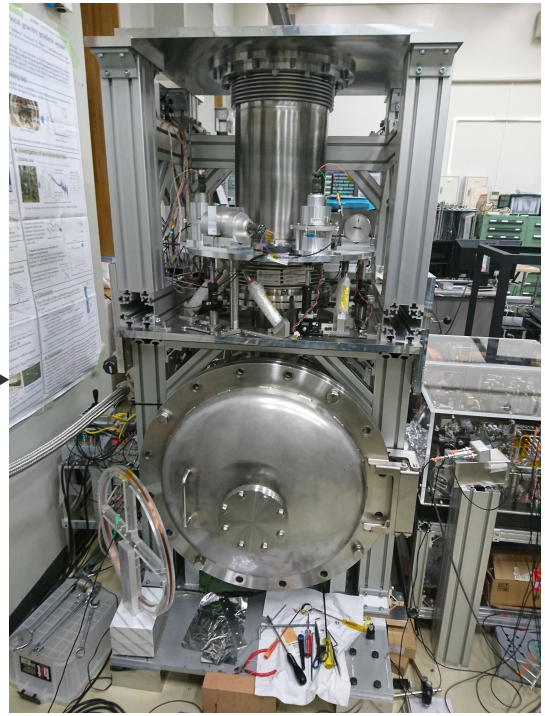
2018 Dec.

- Master Thesis
- Resonance modes
  - x: 5 Hz
  - y: 6 Hz
  - z: 17 Hz



2019 Apr.

- Best Performance
- Resonance modes
  - x: 13 Hz
  - y: 14 Hz
  - z: 32 Hz

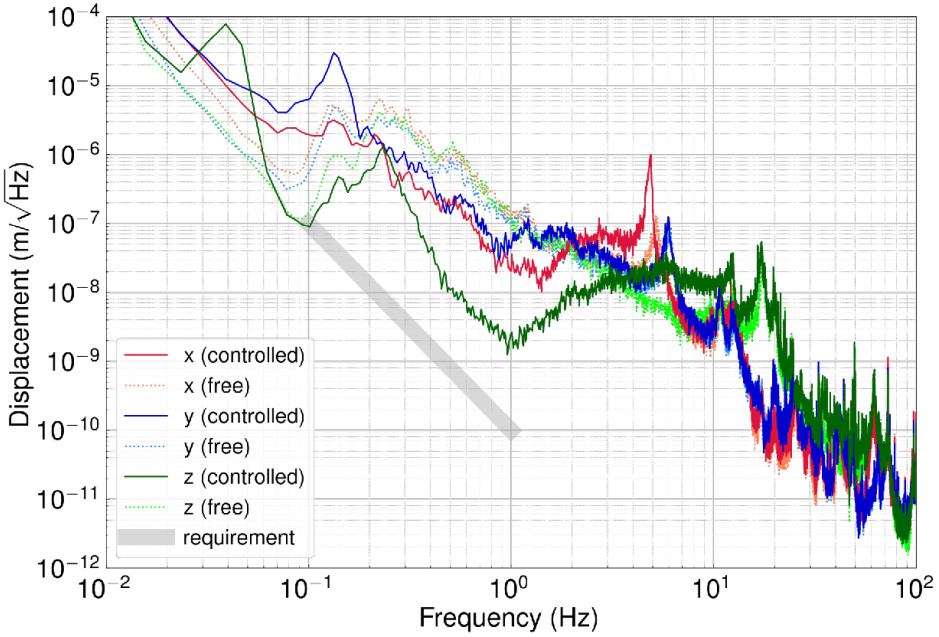


2019 Jul.

- With Suspension
- Resonance modes
  - x: 15 Hz
  - y: 18 Hz
  - z: 11 Hz

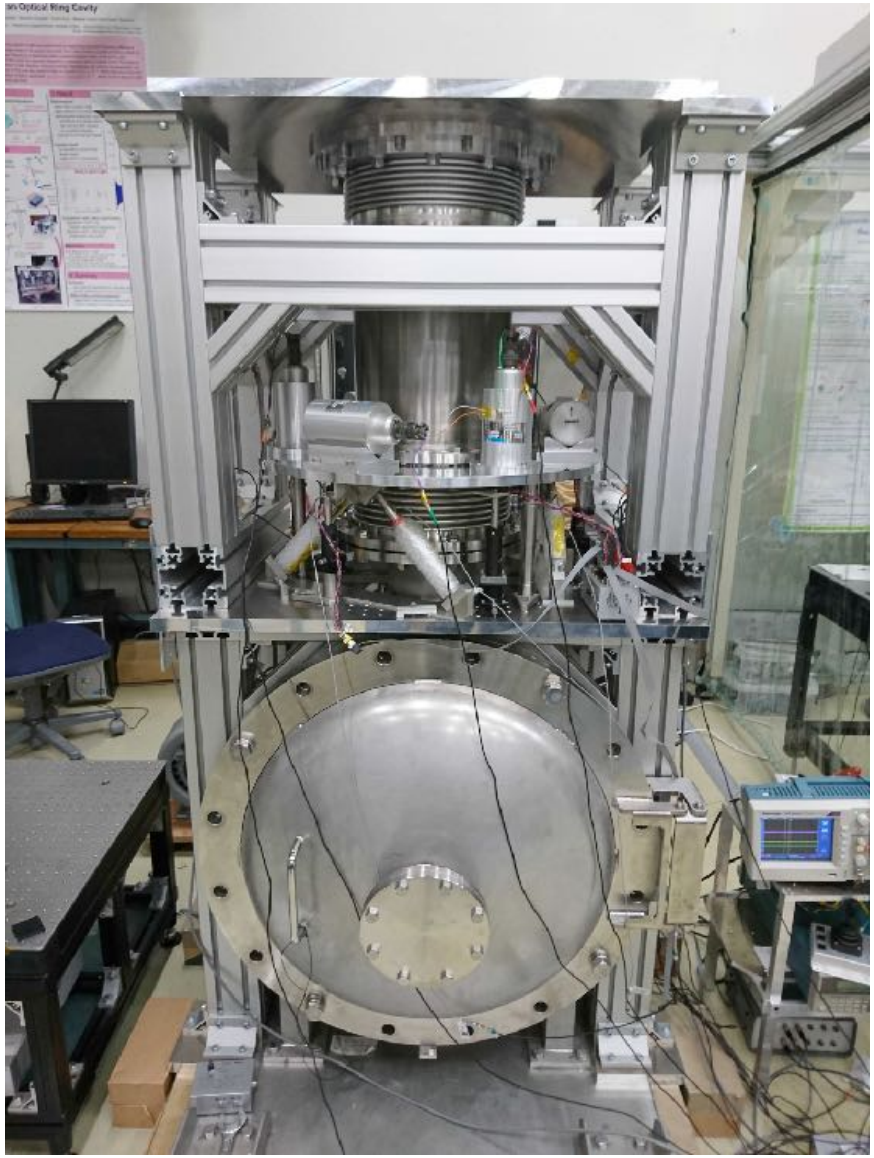
1st Frame

- Terrible Frame
  - Apparently weak structure
- Original chamber frame
  - Basically same as that of Phase-II TOBA
- Used in my master thesis



2nd Frame

- After submitting my thesis,
  I designed and installed this new frame
  - Stiffer support
  - No caster



Installed to TOBA Main Chamber

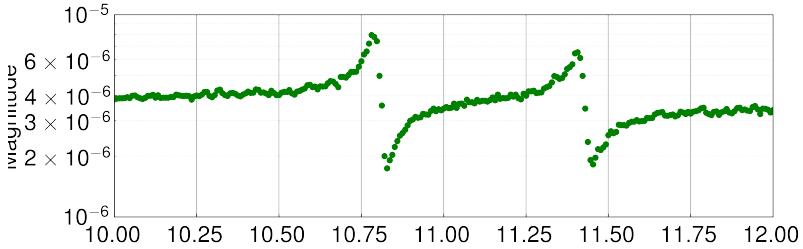
- Installed to TOBA main chamber with suspensions and the cryostat
- Basically same frame as 2nd one, but some parts were omitted due to accessibility
- Q value of parasitic resonances got higher than before

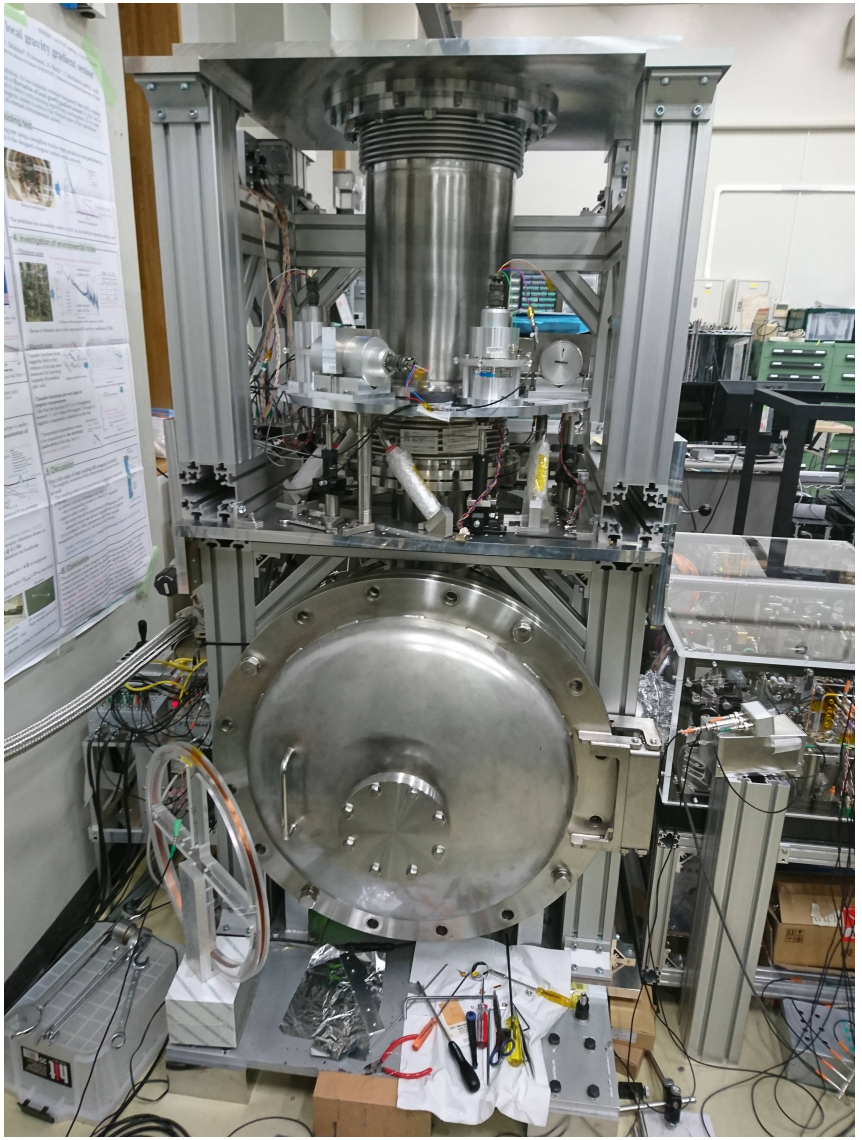
	x	y
f1 (Hz)	13.5	13.8
Q1	9	13
f2 (Hz)	15.1	15.2
Q2	10	16

→

	x	y
f1 (Hz)	15.4	18.4
Q1	67	101
f2 (Hz)	16.7	19.1
Q2	182	2000

- New resonance mode appeared in z





What I Will Do in Thesis

My plan in my Ph.D Thesis

- Controlling AVIT with the cooler running
  - Demonstrating the heatlink vibration isolation
  - Discuss some difference with/without the cooler running

- Vibration isolation performance: achieve the current best level
  - Check parasitic resonances again → modify filter design
  - Identify system response
    - With a student from Fuculty of Engineering
  - Establish how to prepare and operate AVIT

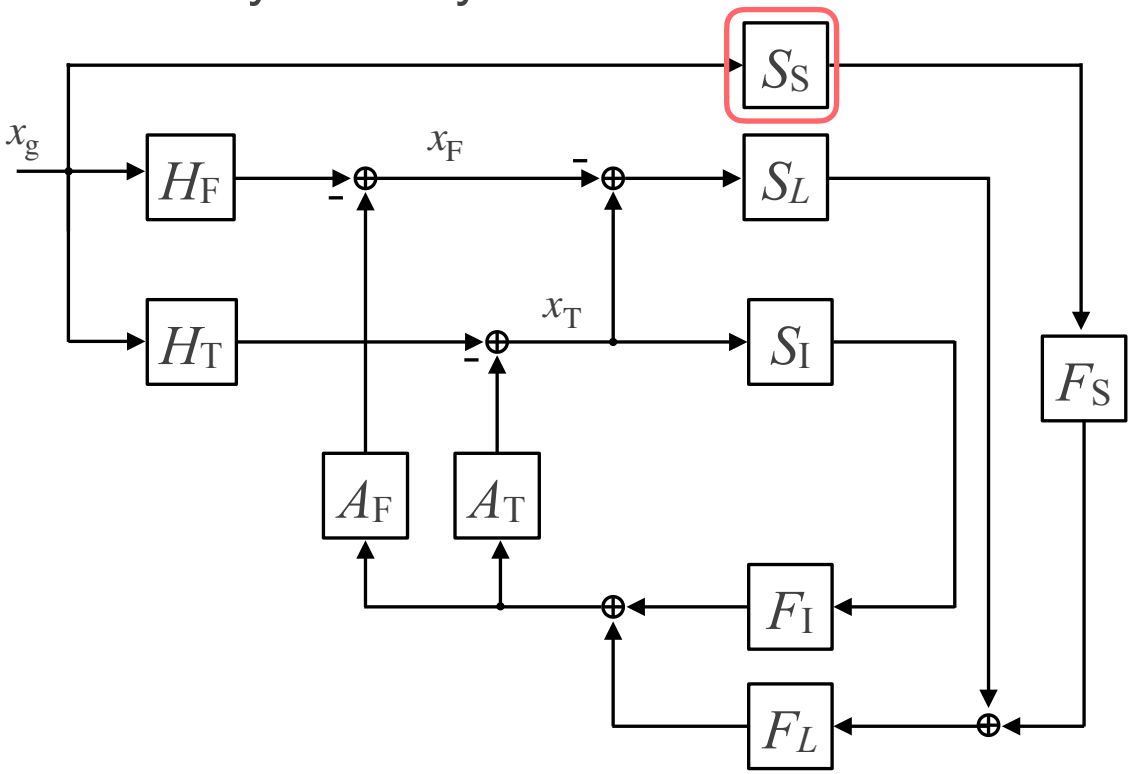
Some New Ideas

- From now I'll show some ideas for AVIT
  - Some are not considered well. Maybe wrong.

- Ideas:
- Feedforward mitigation in low frequency
- Active damping of mechanical resonance mode
- Suspended inertial sensor

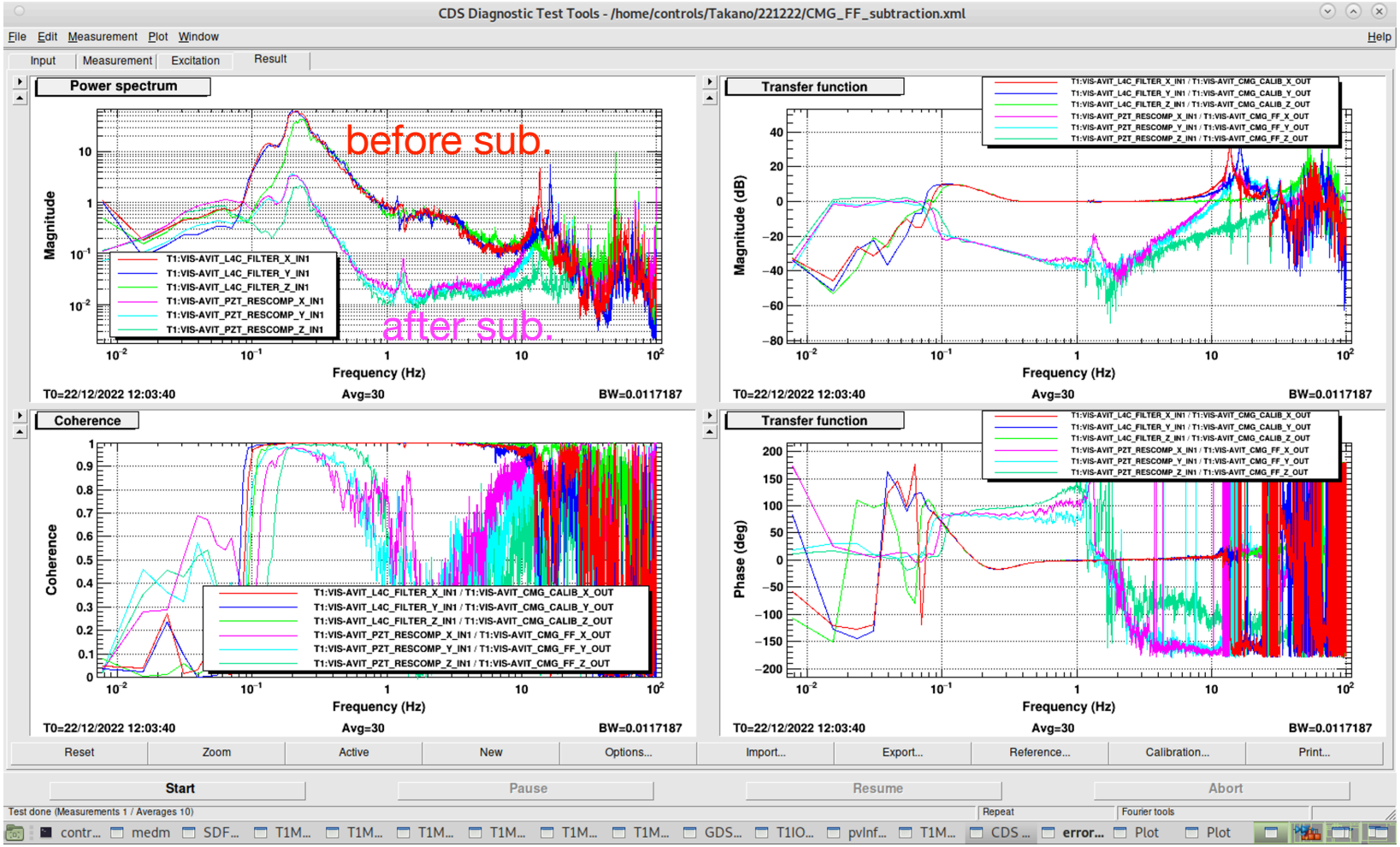
Feedforward in Low Frequency

- Below 1Hz there are large coherence between geophone signals on AVIT and seismometer signals on the floor
- Is it necessary to reduce vibration by feedback?
- Is feedforward enough for low frequency region?
- In GW community actually this is called **sensor corrention**



Online Subtraction

- I tried subtracting seismometer signals from geophone signals online

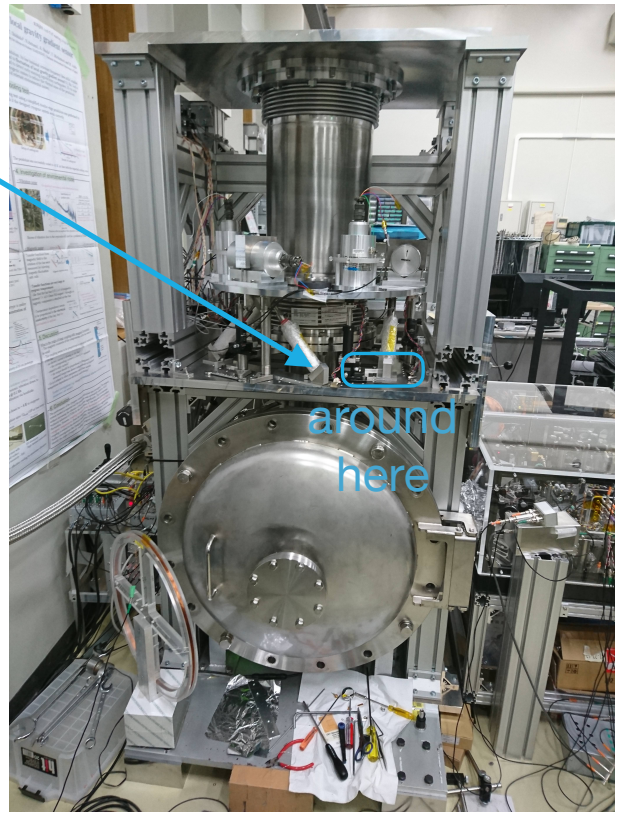


Active Damping of Mechanical Resonance

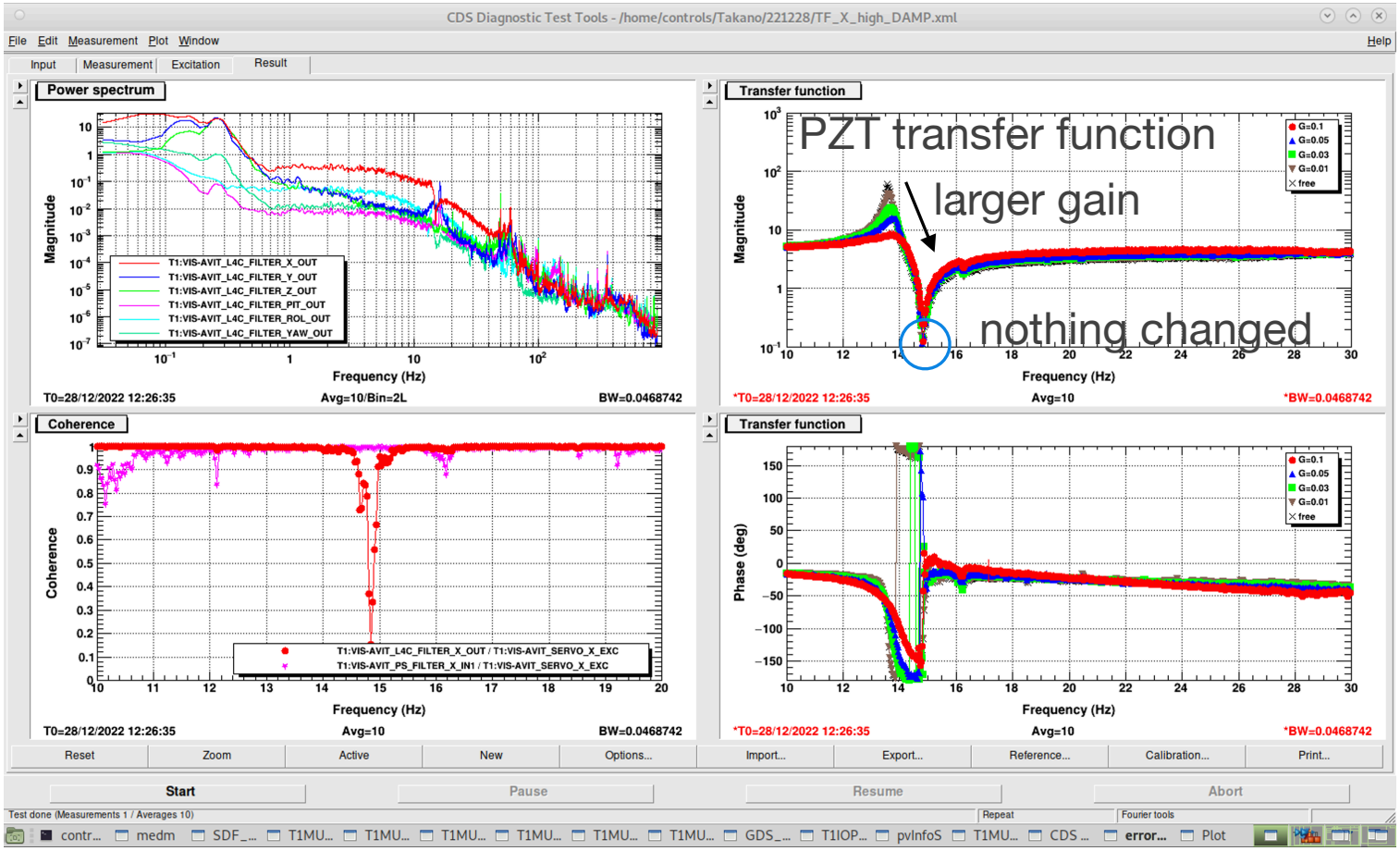
How to damp resonance mode of the support frame?

- Add damper to the frame
- Make the frame more lossy material
- Damp resonance actively?

- I put a geophone on the frame (not AVIT) and fedback its signal around resonance frequency to PZT actuators



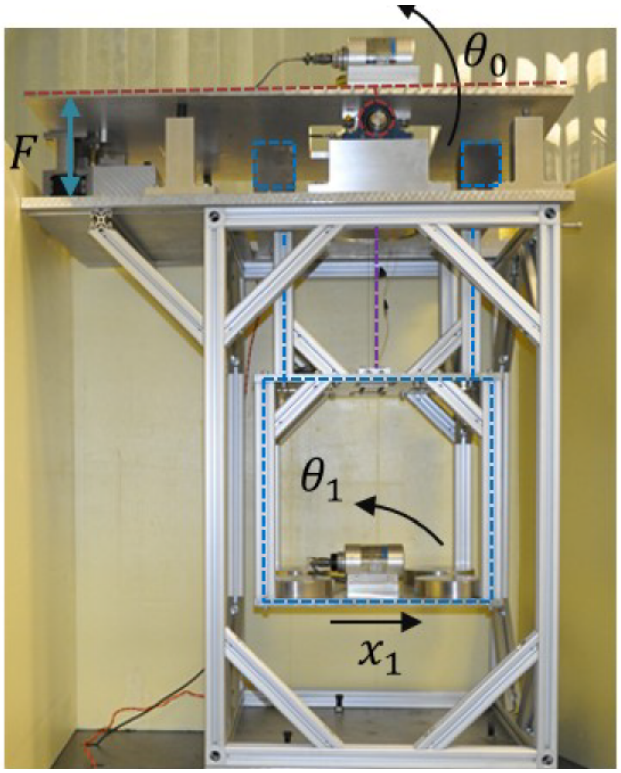
Active Damping



- Increasing gain…
  - Peak: damped
  - Dip: not changed
- Not sure whether it works when I close main control loops…

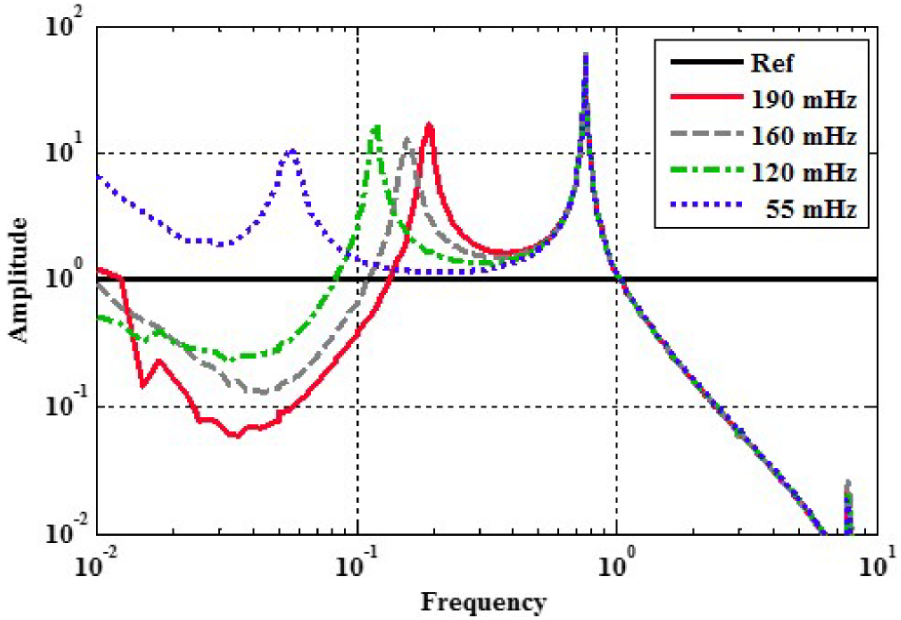
Suspended Inertial Sensor

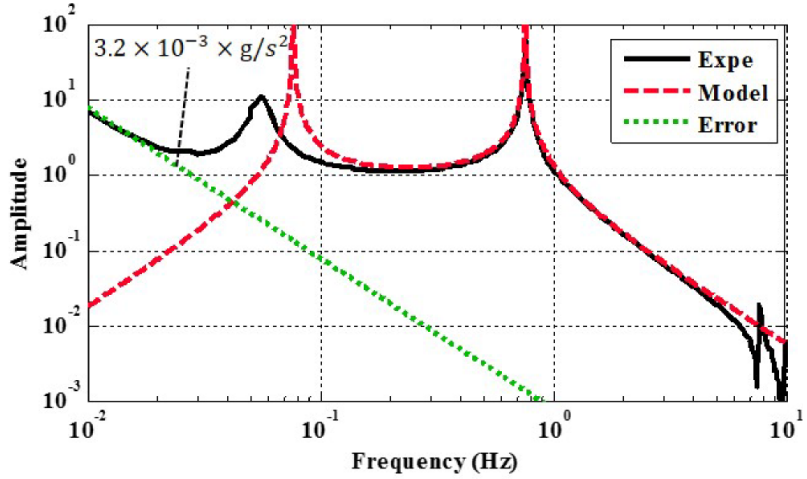
- Actually not my idea…
- From this paper:
  "Modeling and experiment of the suspended seismometer concept for attenuating the contribution of tilt motionin horizontal measurements"
- Suspend a inertial sensor to reduce tilt-horizontal coupling
- They could reduce the tilt coupling, but translational coupling is band-limited

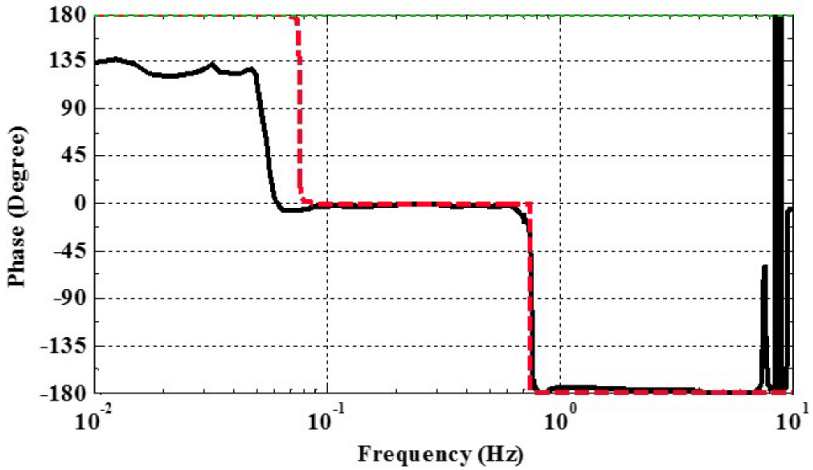


Band-limited Response

- Principle was demonstrated
- Above 0.1 Hz the response is well matched to the model
- Which is better, to make this sensor or a tiltmeter?







Summary

- For years I have worked on development of AVIT
- Currently the performance is limited by:
  - low frequency: tilt-horizontal coupling
  - high frequency: mechanical resonance mode
- I attacked there problems, but not fully solved. Need more improvements
- My plan about AVIT in my thesis:
  - Operate with cooler running
  - Measure difference with/without the cooler
  - Reproduce the current best sensitivity
- I also showed some new ideas
  - Not sure they will work or not
- If you are interested in AVIT, take over my research…