Ph. D. defense
博士論文審査会

A Study of Baseline Compensation System for Stable Operation of Gravitational-wave Telescopes

（重力波望遠鏡の安定稼働のための
基線長補償システムの研究）

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"A Study of Baseline Compensation System for Stable Operation of Gravitational-wave Telescopes"

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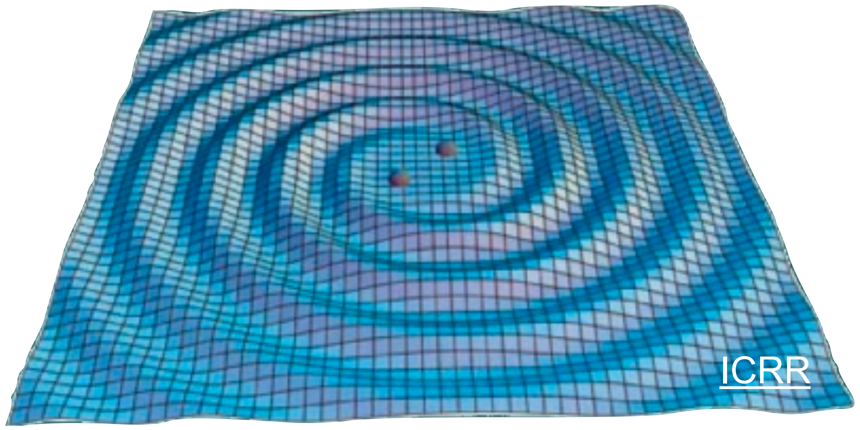
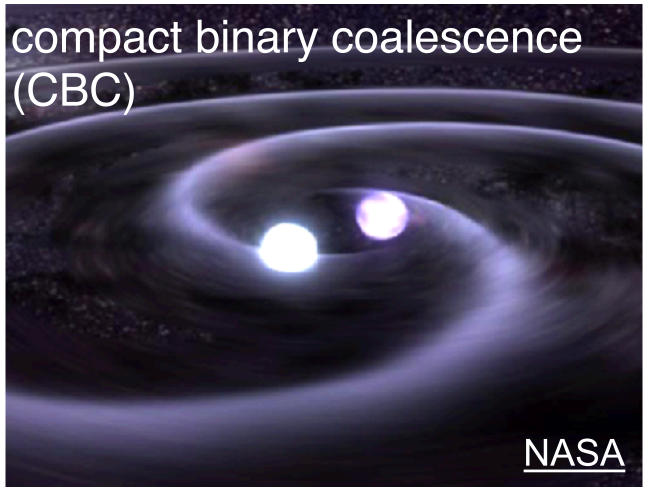
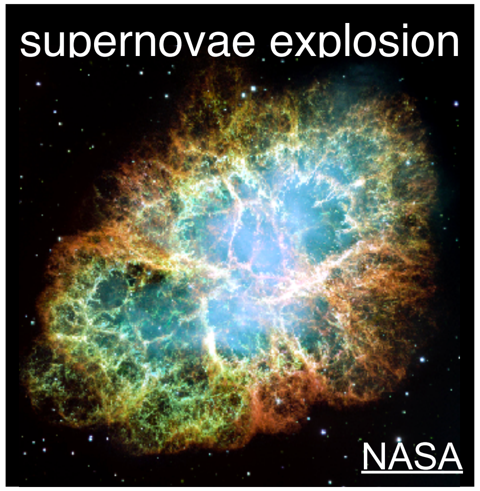
Gravitational-wave (GW)



GW
- Ripple of space-time
- Generated by compact and massive objects

GW sources
- Binary black hole (BBH) merger
- Binary neutron star (BNS) merger
- Supernovae explosion

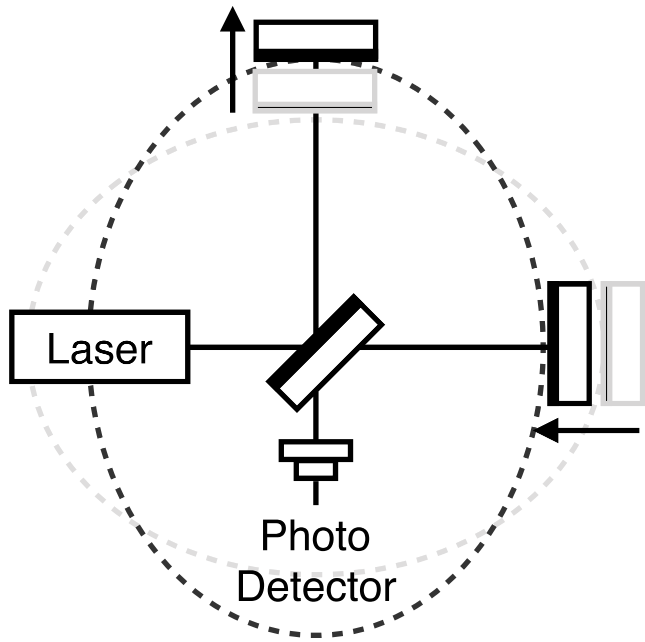




Fruitful informations for physics
- Testing the general relativity
- Nuclear equation of state
- A new observation tool

GW observations bring new informations of the universe to us.

GW Detector

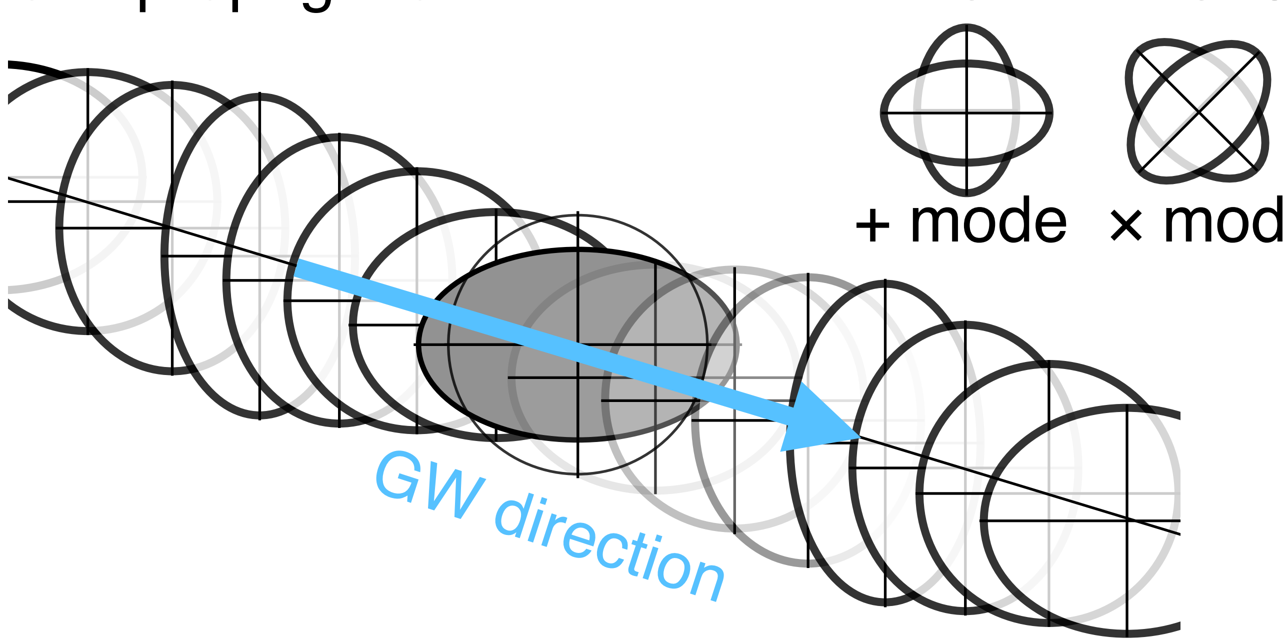


Michelson interferometer

GW
- Tidal deformation
- Two polarizations

Michelson interferometer
- Differential arm length changes
- Wide antenna pattern

GW propagation

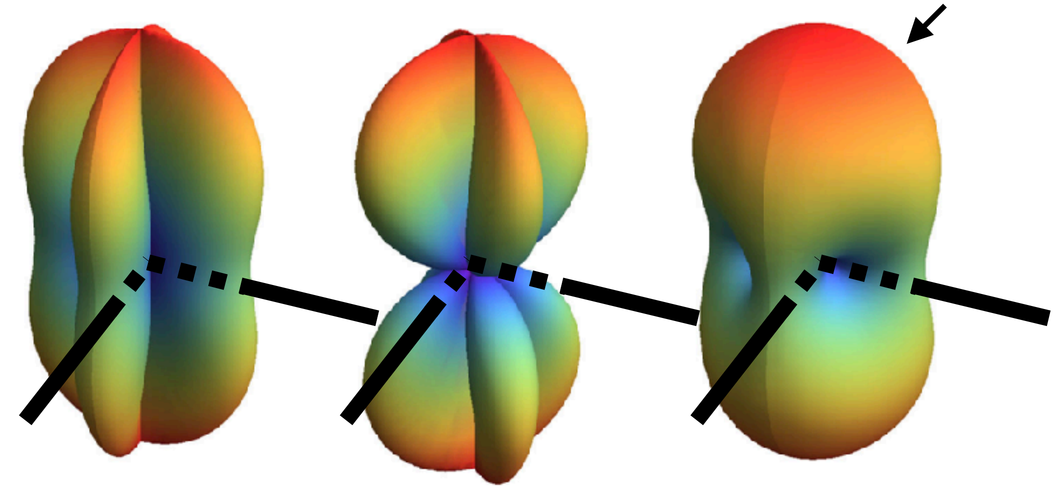


Polarizations

+ mode × mode

Antenna patterns

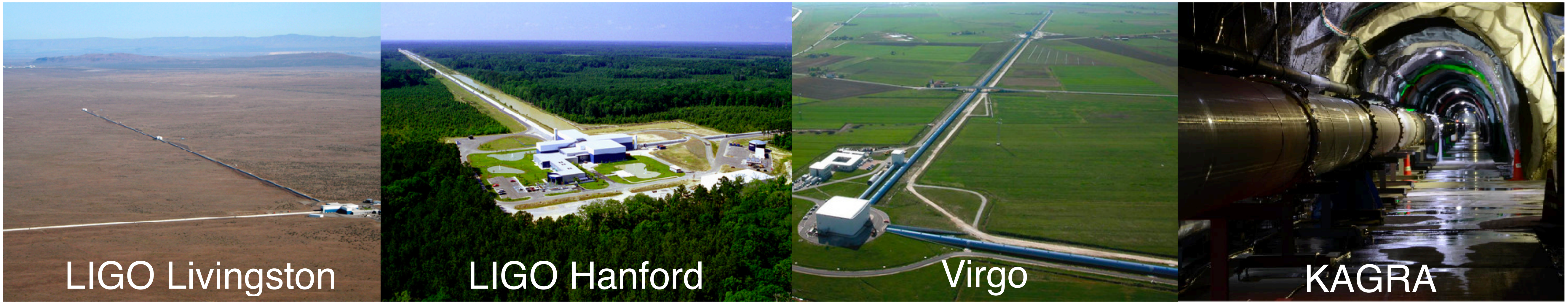
wide directivity



+ mode × mode averaged

We need multiple detectors to determine direction and polarizations.

GW Detectors



Network Duty Cycle
$\fallingdotseq D_1 \times D_2 \times D_3 \times D_4$

(D_i : duty cycle of the i-th detector)

Determination by multiple detectors

- 3 detectors for direction
- 4 detectors for polarization

Network duty cycle is below 50 %

- Lost the direction
- Lost the polarization
- Lost rare “Near-Earth” events

↓

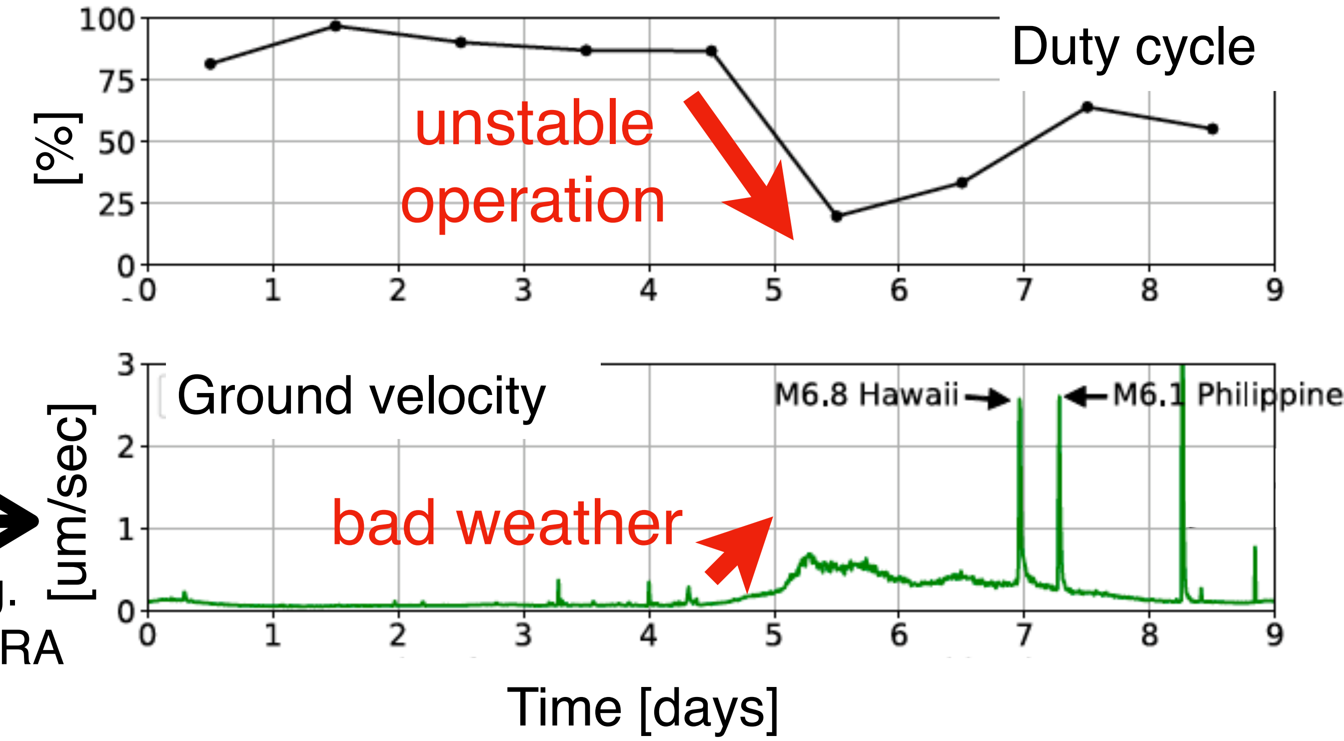
Duty cycle is important

Seismic Noise Limiting the Duty Cycle

Problematic seismic motions (< 1Hz)

- Microseismic motions (0.1 - 1 Hz)
    - Ocean wave
    - Depends on weather
- Large earthquakes (0.03 - 0.1 Hz)
    - Not frequent (1/month)
    - Continue 2-3 hours
- Earth tides (1/2 day)
    - RMS amp. ~ 100 um
    - Excess actuator range

e.g. KAGRA



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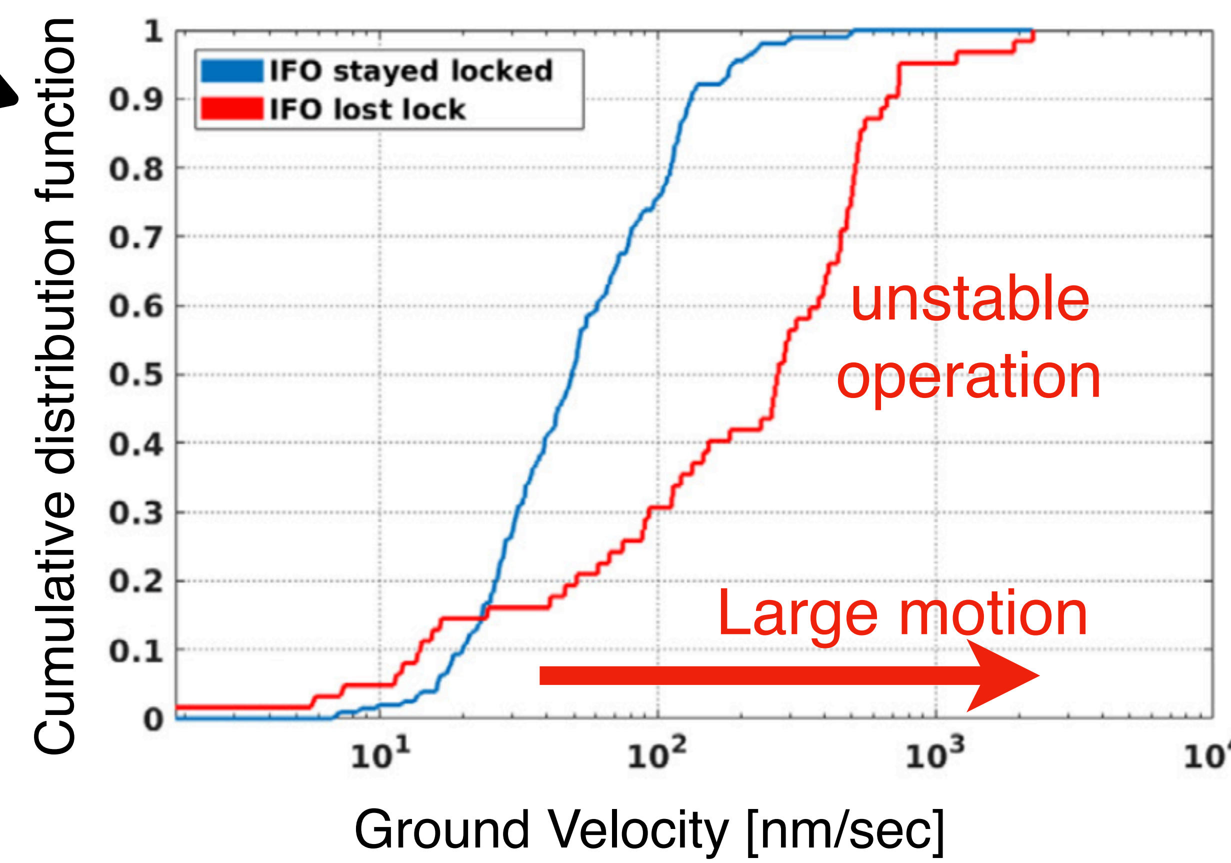
e.g. LIGO



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All GW detectors are suffering with the seismic motions < 1 Hz.

Difficulties of the GW detector operation

"Dual-recycled Fabry–Pérot Michelson interferometer"

- Three optical resonance cavities
- Must keep on resonance
- Suspended mirrors

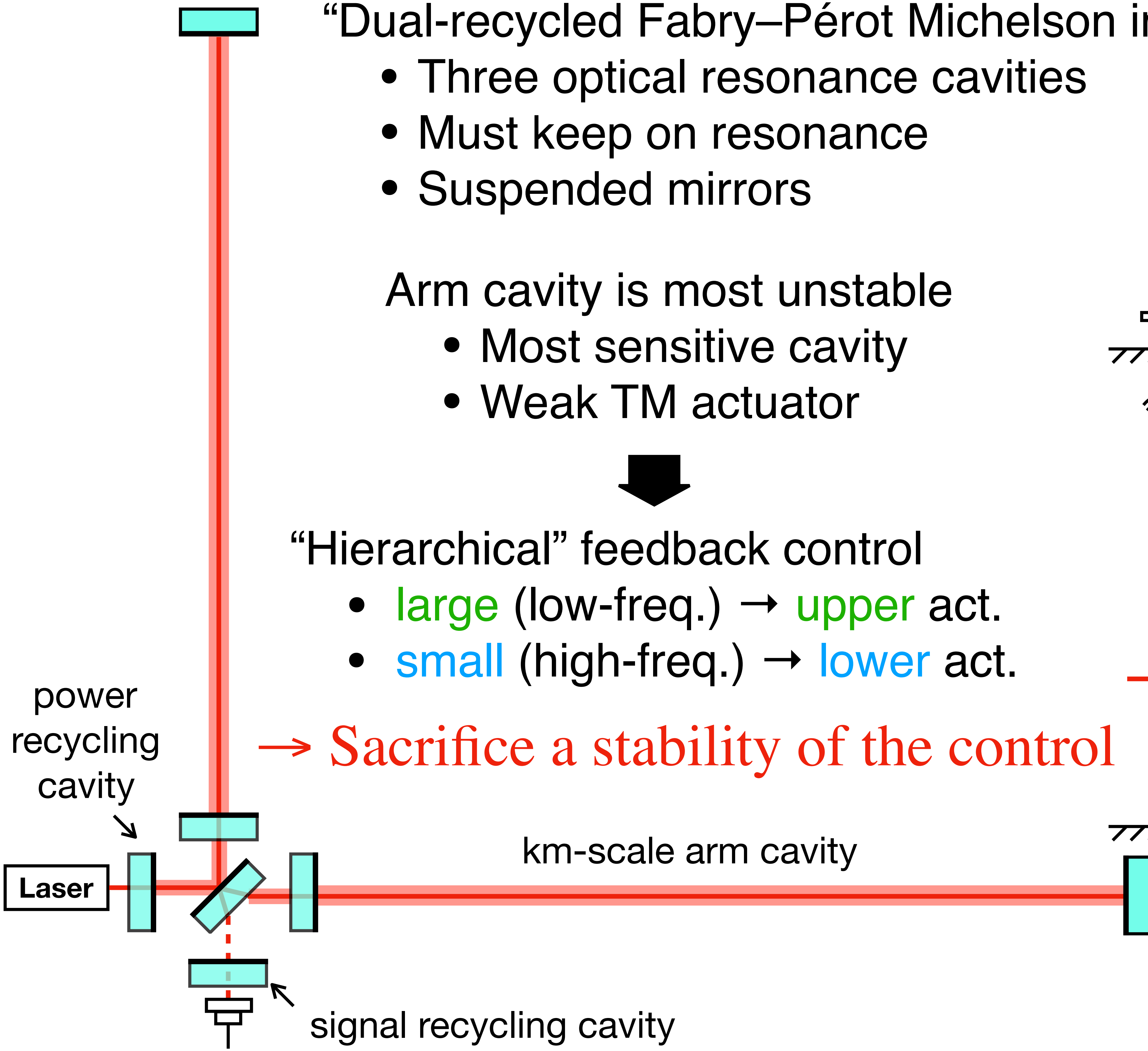
Arm cavity is most unstable

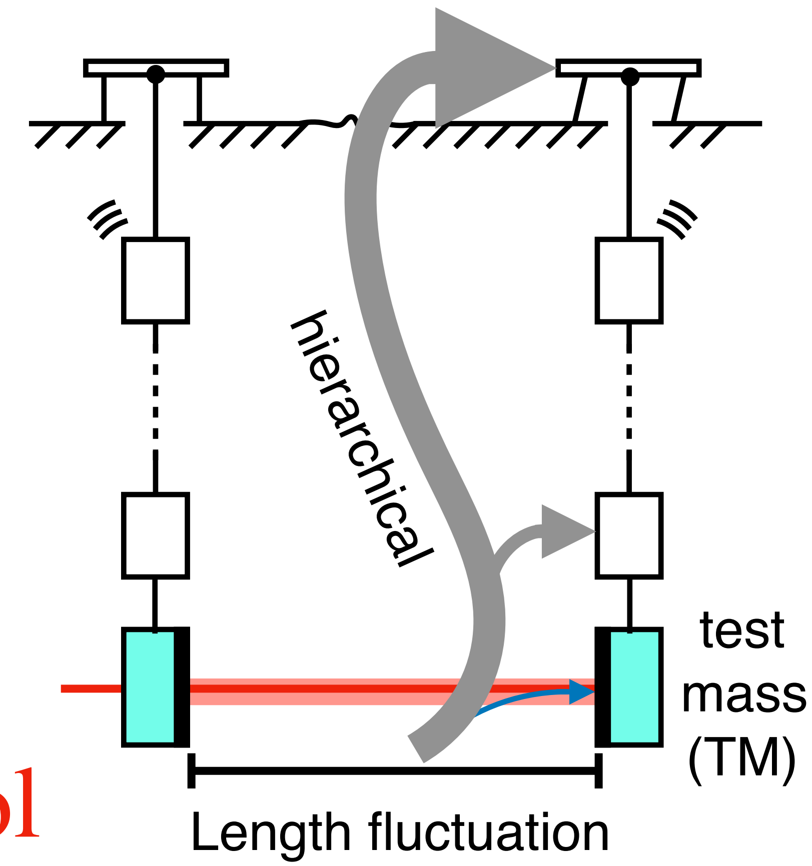
- Most sensitive cavity
- Weak TM actuator

"Hierarchical" feedback control

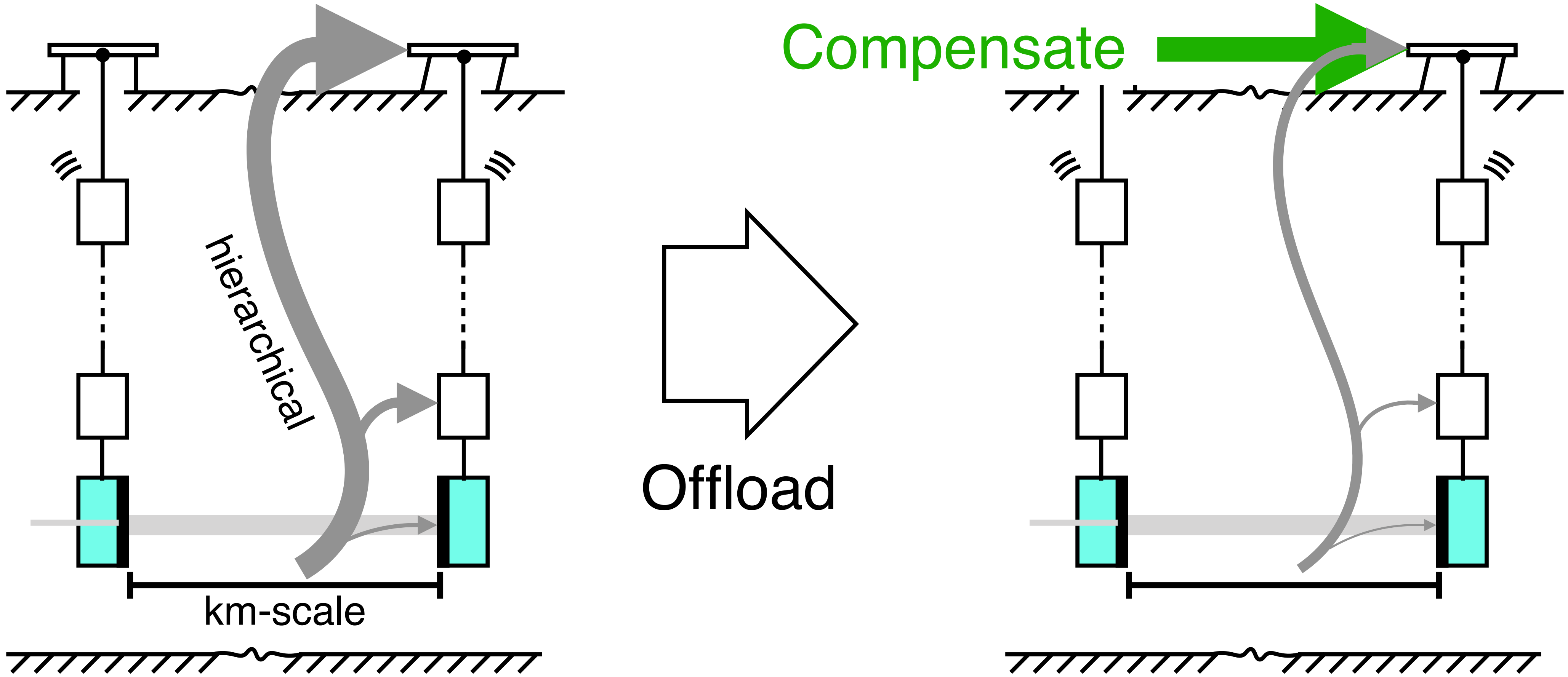
- large (low-freq.) → upper act.
- small (high-freq.) → lower act.

→ Sacrifice a stability of the control





Motivation of low-frequency seismic isolation



Profits of offloading

- saturation of weak actuators
- stability of control loop

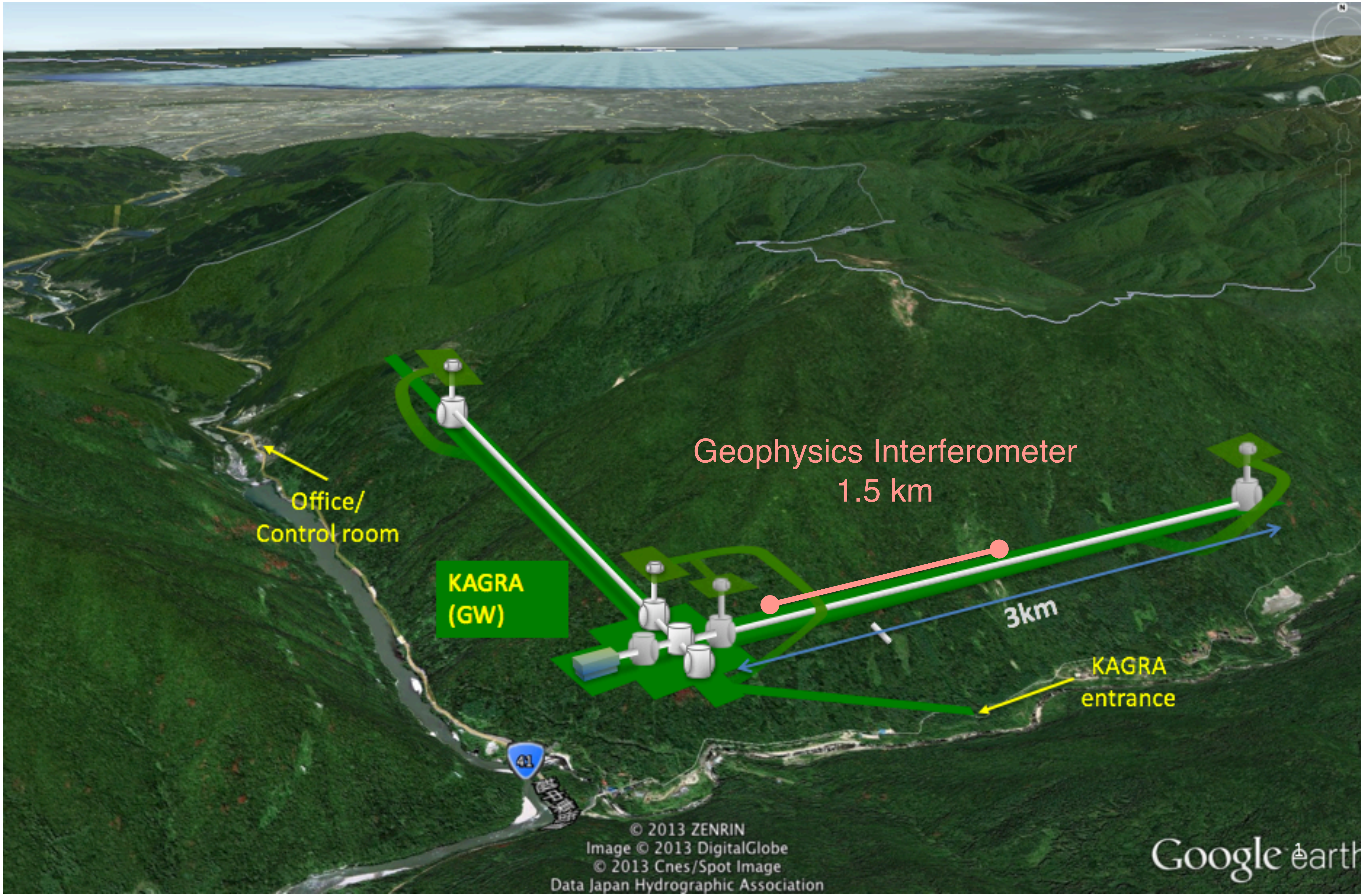
Baseline sensors for the compensation (< 1Hz)

- Two seismometers : indirect, no sensitivity
- Strainmeter : direct, enough sensitivity

KAGRA has a strainmeter named "Geophysics Interferometer"

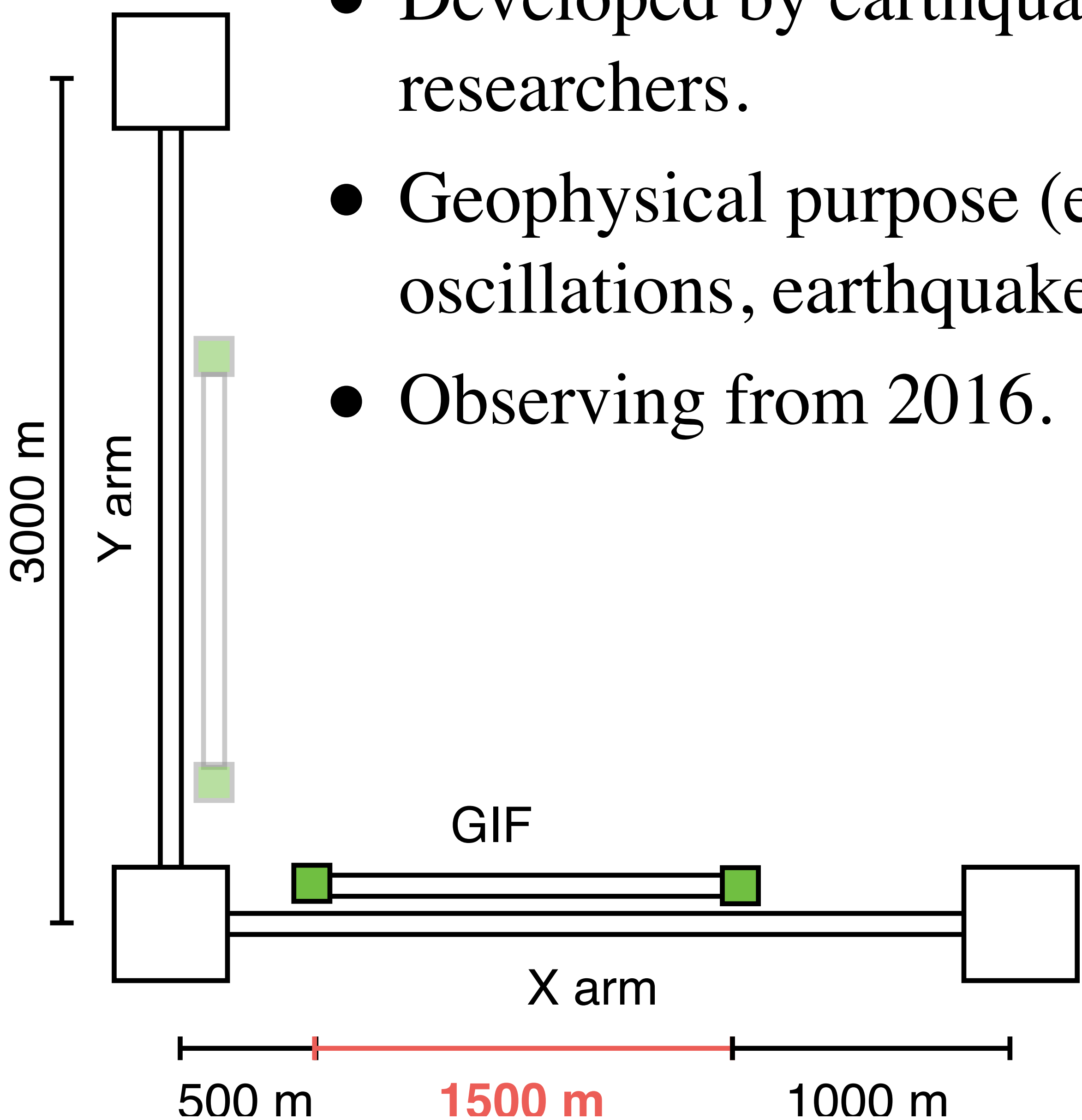
Contents

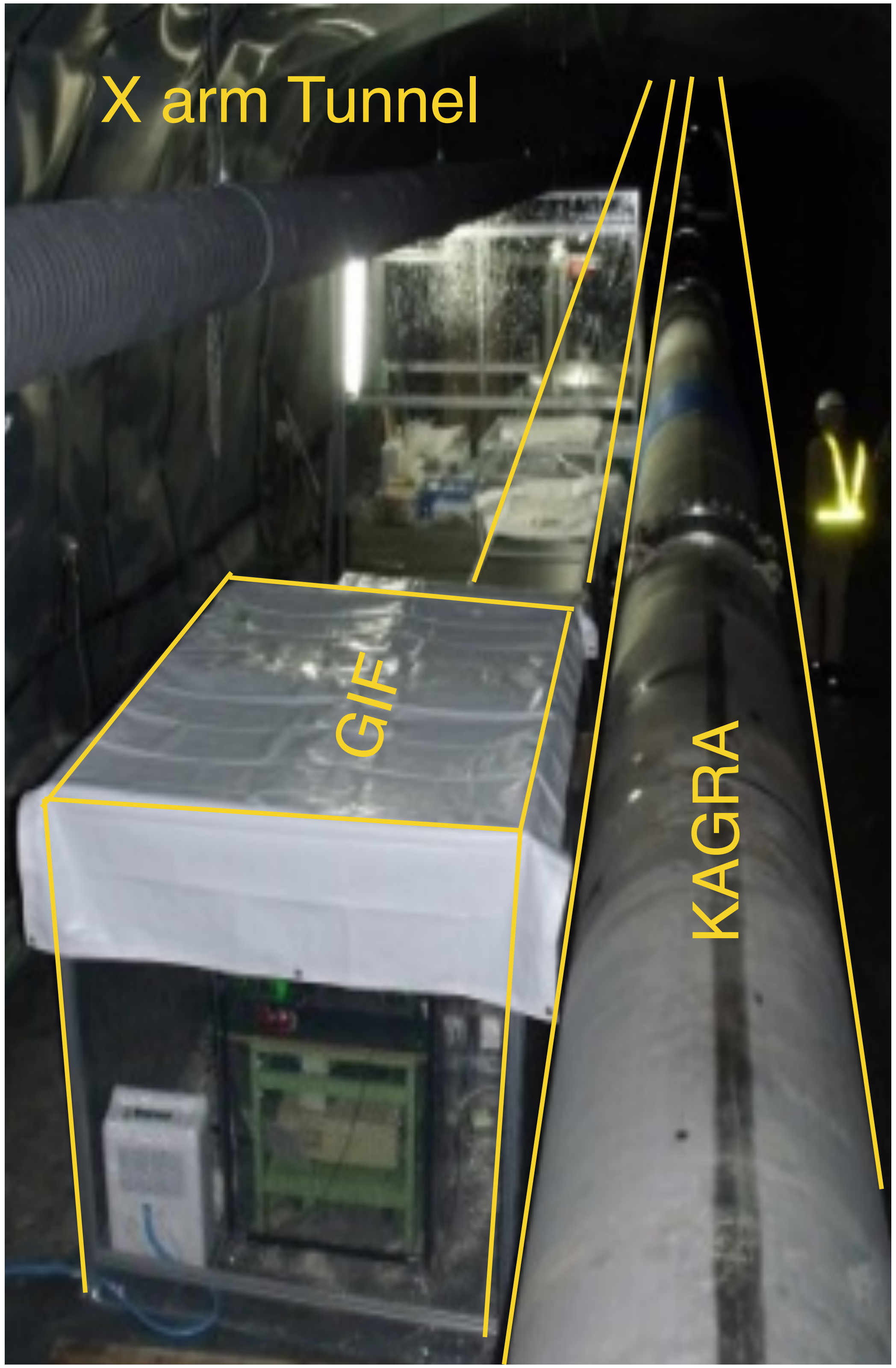
KAGRA and Geophysics Interferometer



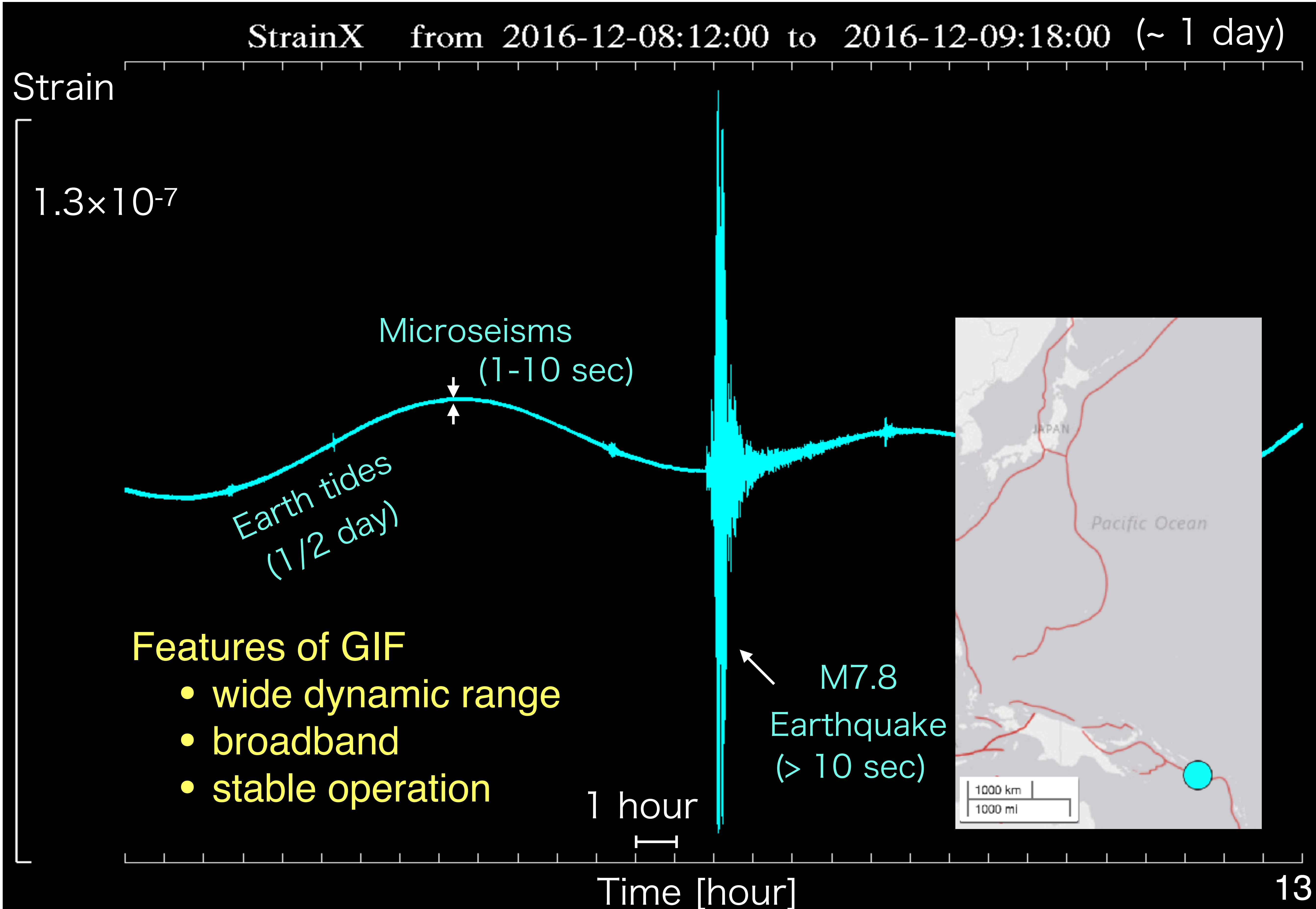
Geophysics Interferometer (GIF)

- A 1500 m strainmeter
- Developed by earthquake researchers.
- Geophysical purpose (earth oscillations, earthquakes, …)
- Observing from 2016.





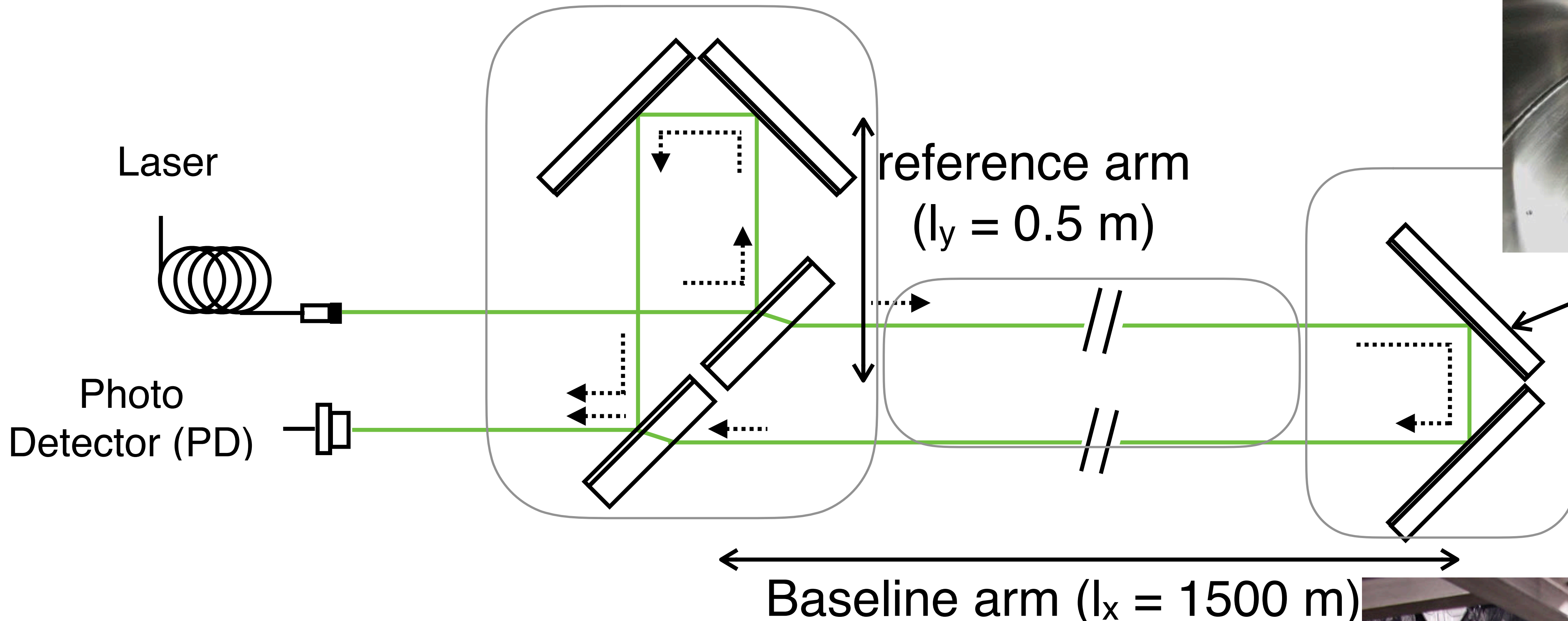
Deformation measured by GIF

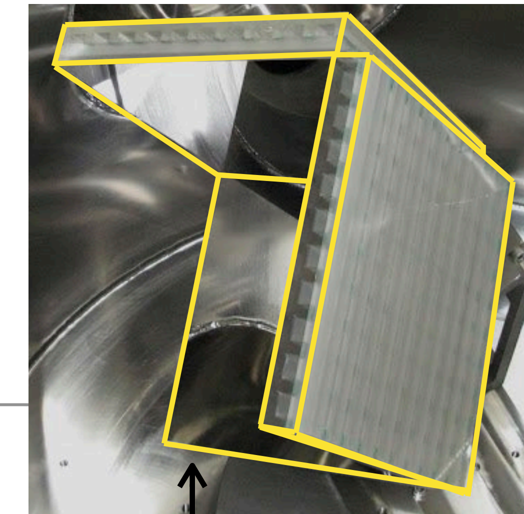


Features of GIF

- wide dynamic range
- broadband
- stable operation

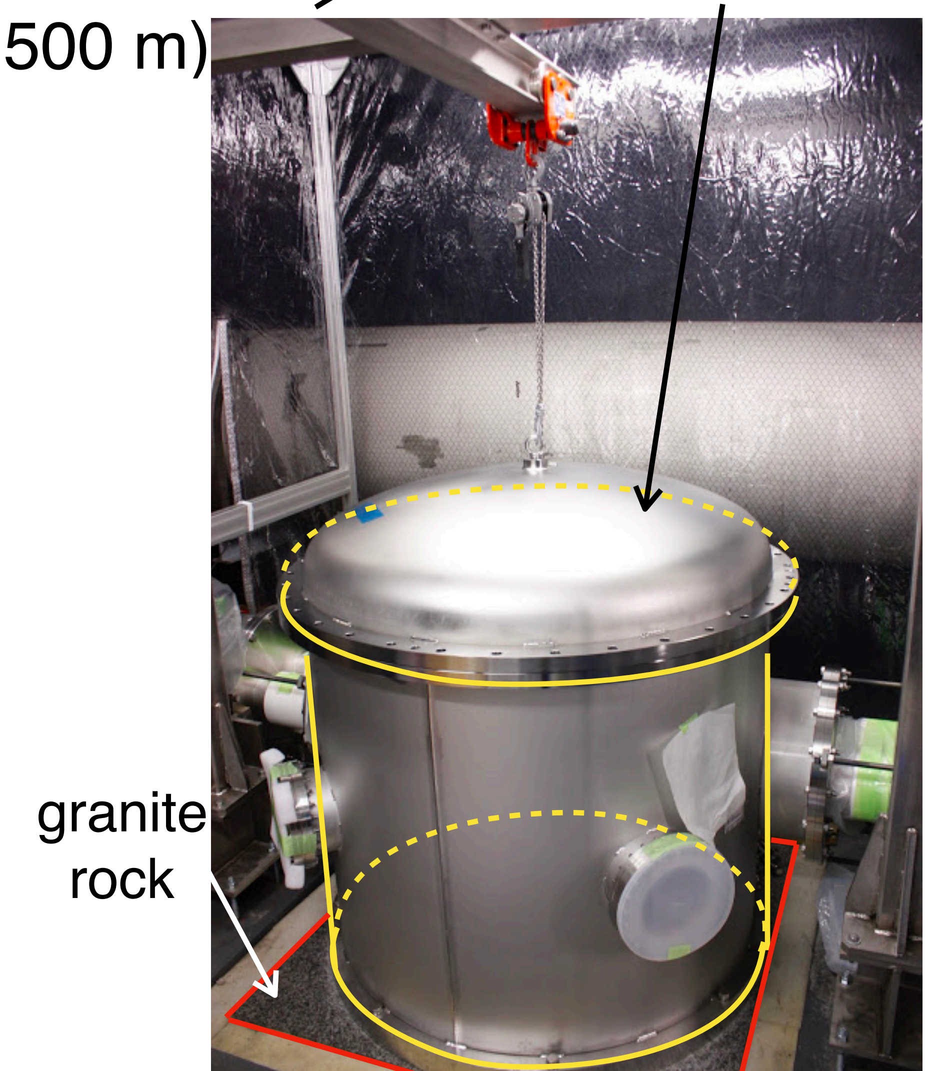
Geophysics Interferometer (GIF)





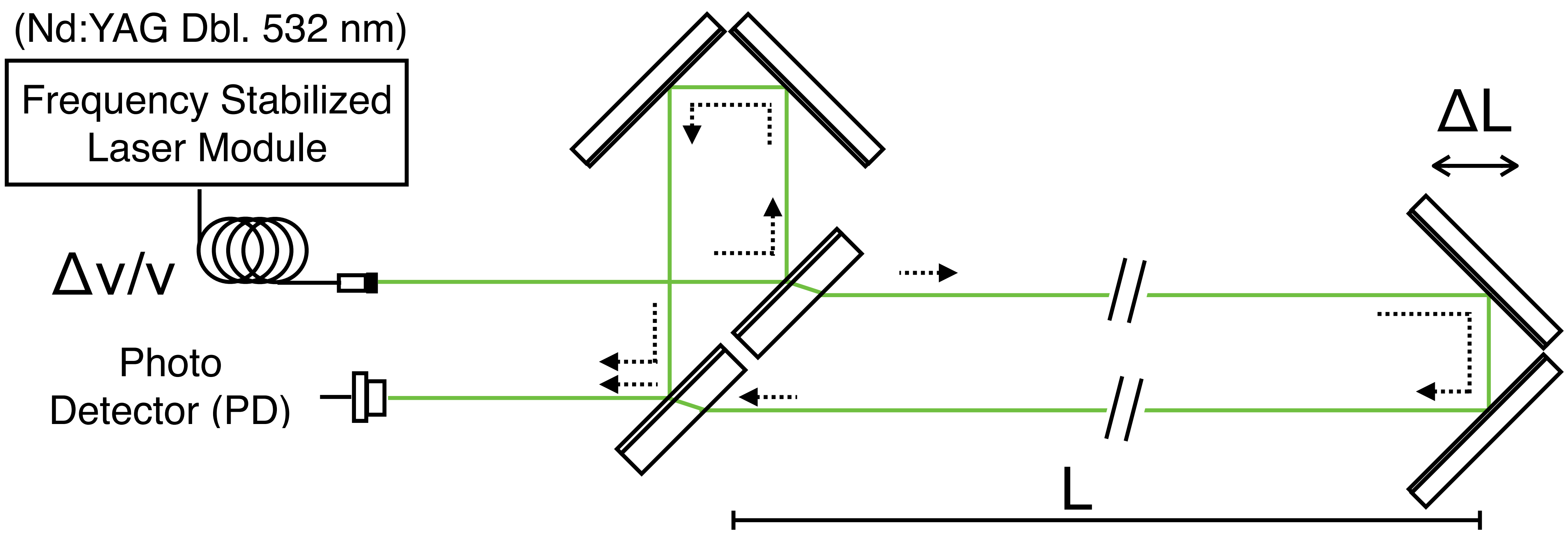
1500 m asymmetric Michelson interferometer

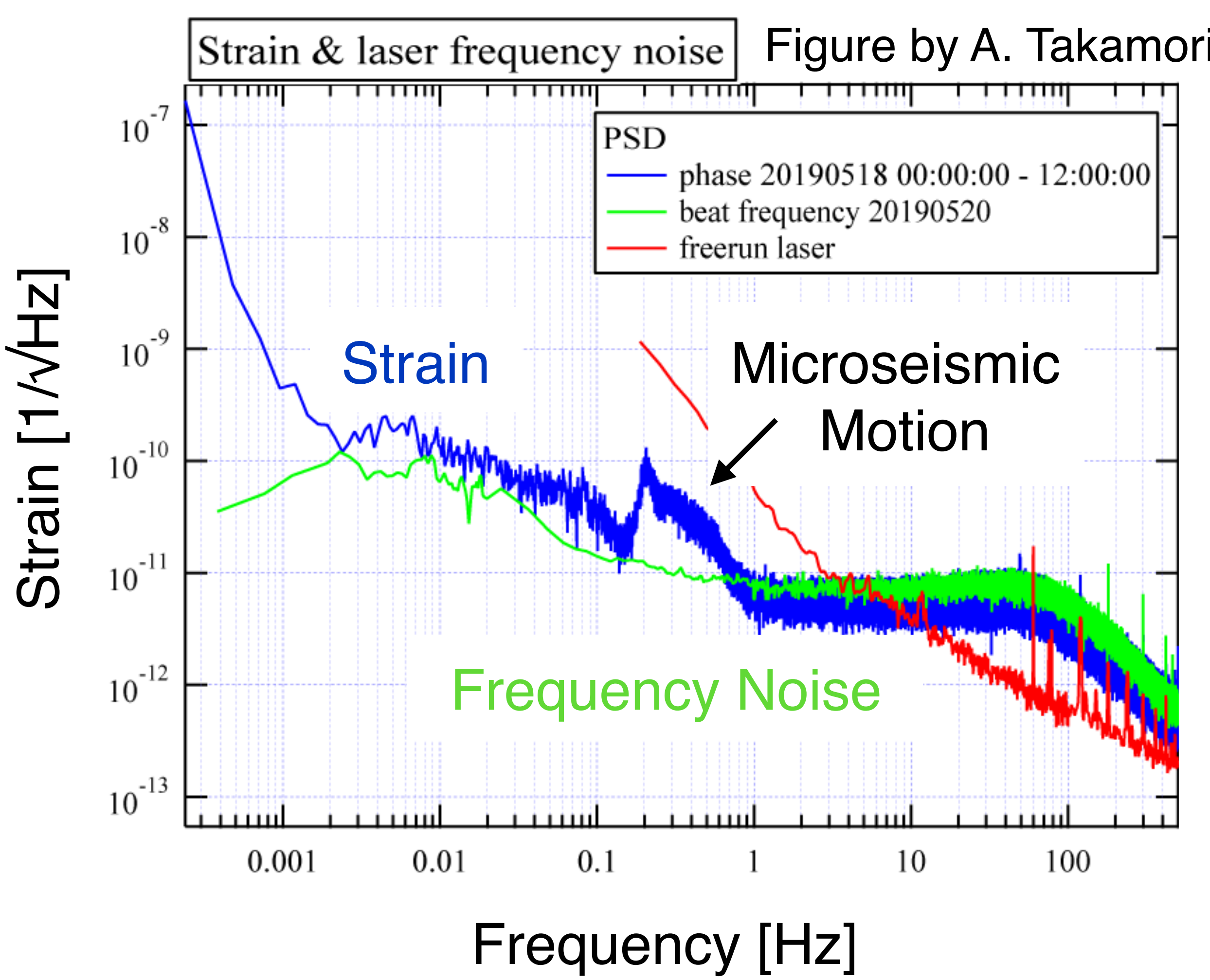
- Sensitive to differential arms length; l_x - l_y
- Use corner cubes
- No active alignment control on mirrors
- Mounted on the ground



Direct and stable measurement

Main noise source





Strain resolution

- $\frac{\Delta L}{L} \sim \frac{\Delta \nu}{\nu}$

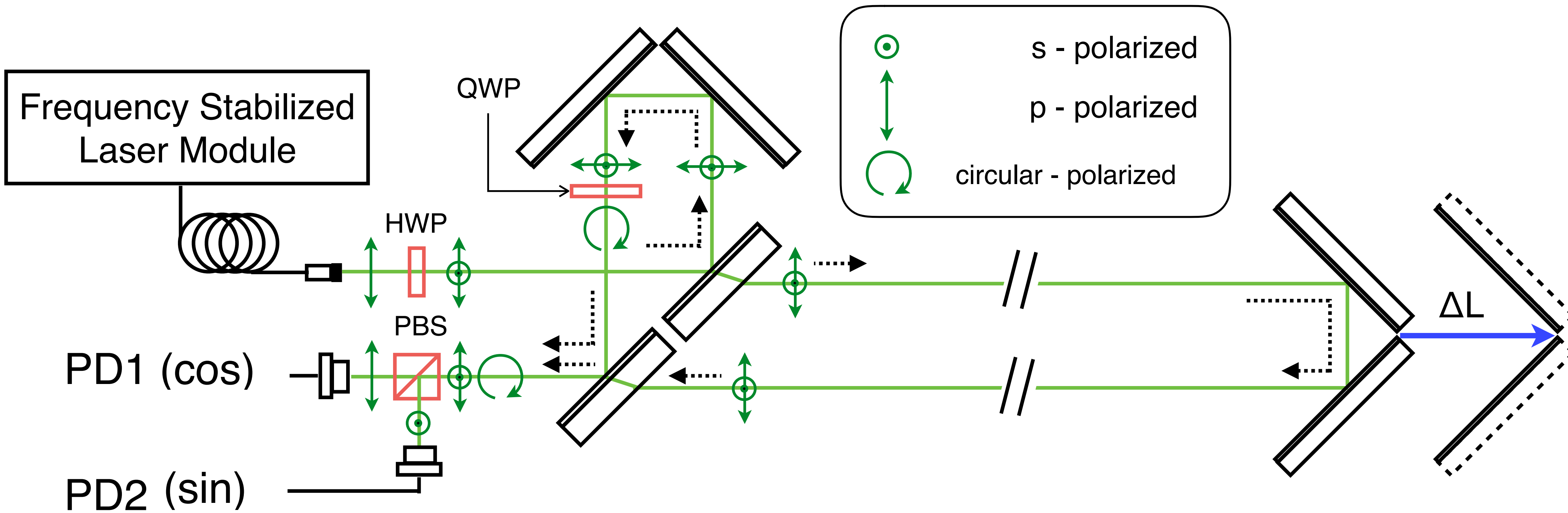
Frequency Stabilized laser

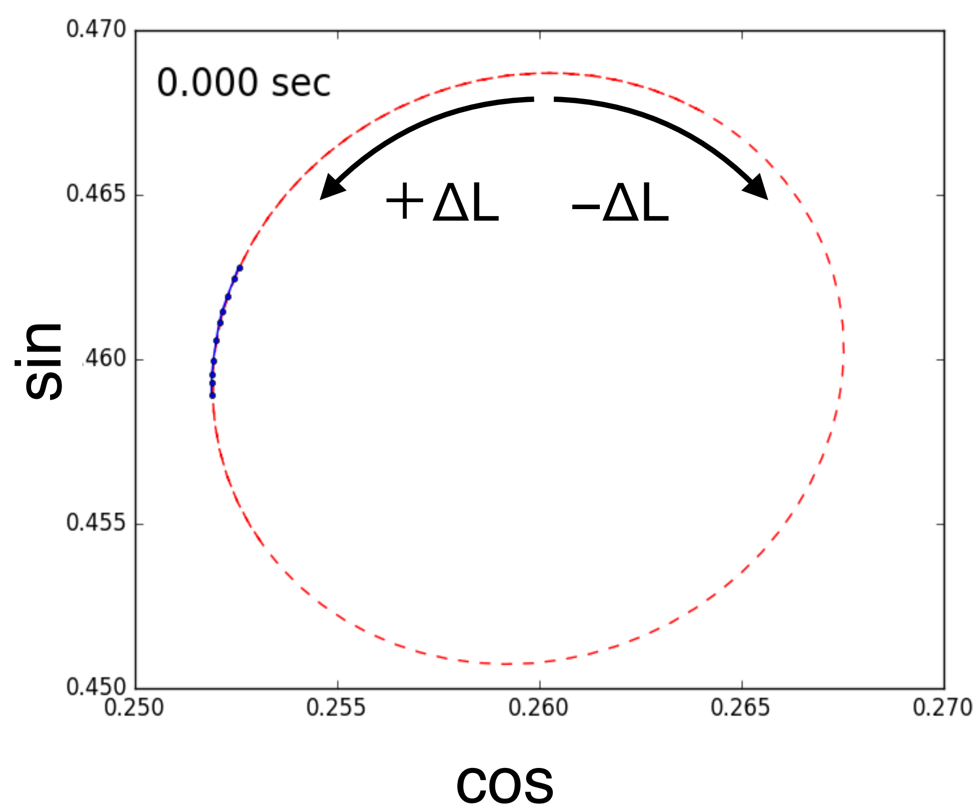
- $\Delta v/v \sim 10^{-11}$

Precise measurement (~10^{-11})

(below microseisms)

Signal detection (Quadrature phase detection)

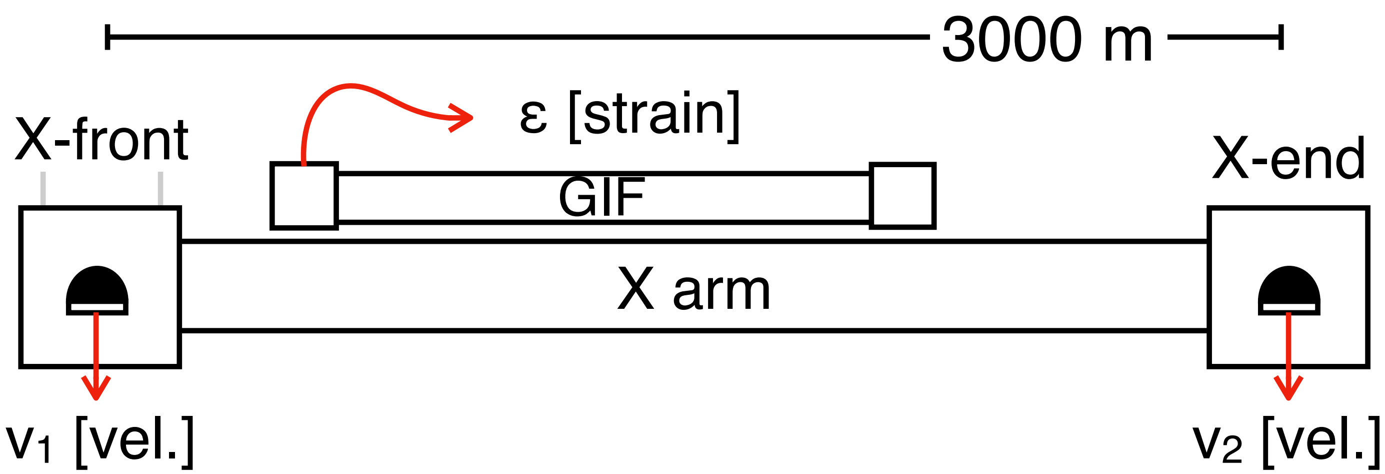




- Two fringe signals; sin and cos
- ΔL → rotation angle
- Need a realtime ellipse fitting

Wide dynamic range measurement

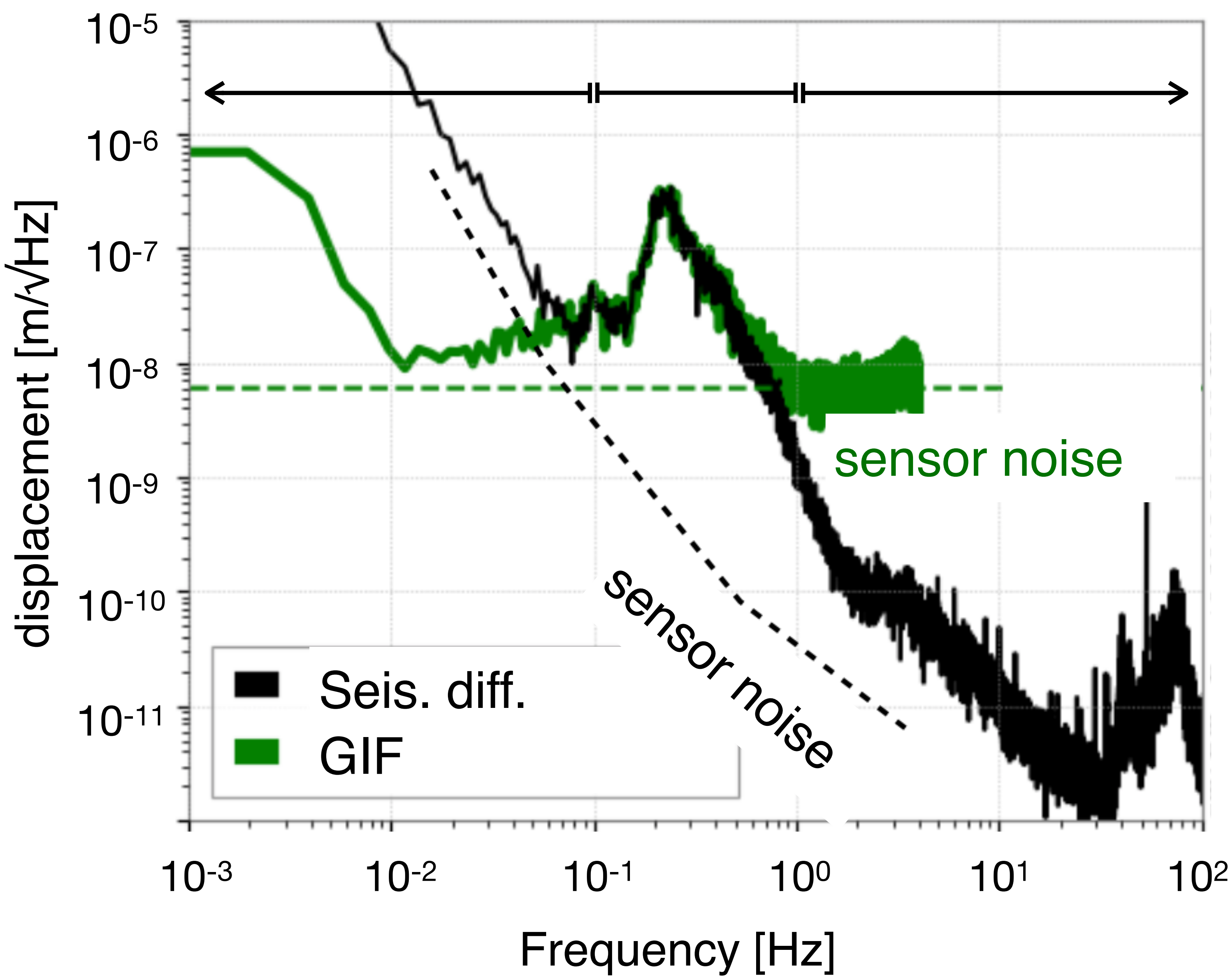
Comparison with seismometer



ΔL measured by two ways

$\Delta L_{3000} = \varepsilon \times 3000$ … GIF

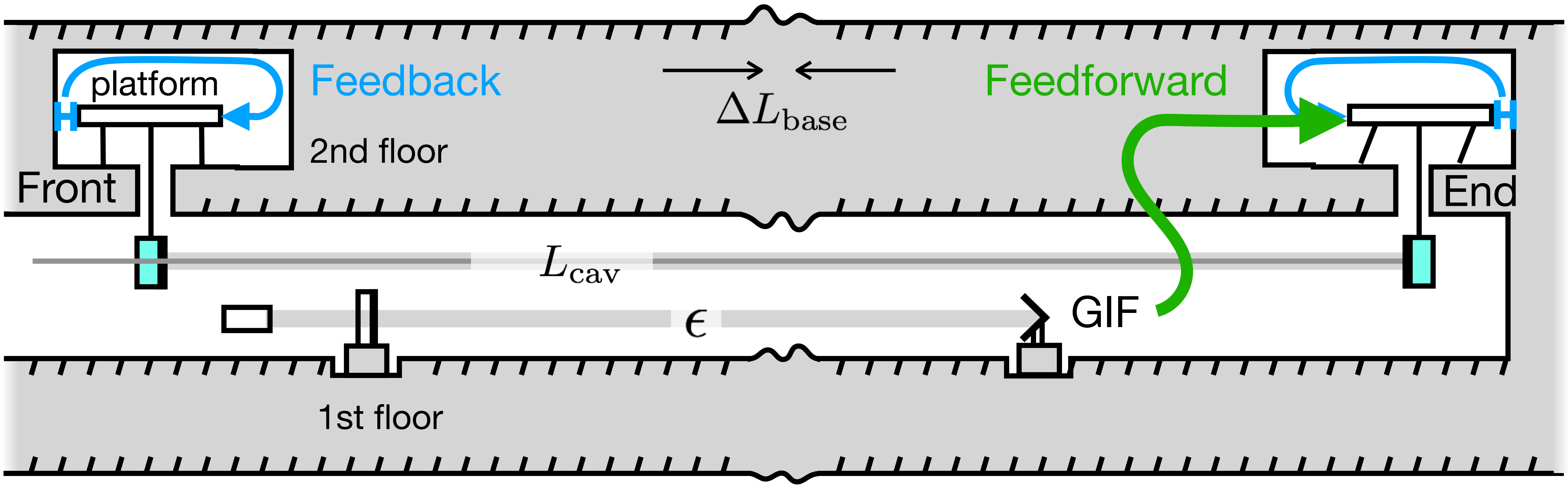
$\Delta L_{3000} = \int (v_1 - v_2)\, dt$ … Seismometer



Strainmeter has a better sensitivity below 0.1 Hz than seismometer

Contents

Baseline Compensation System



sectional view of X-arm tunnel

Scope

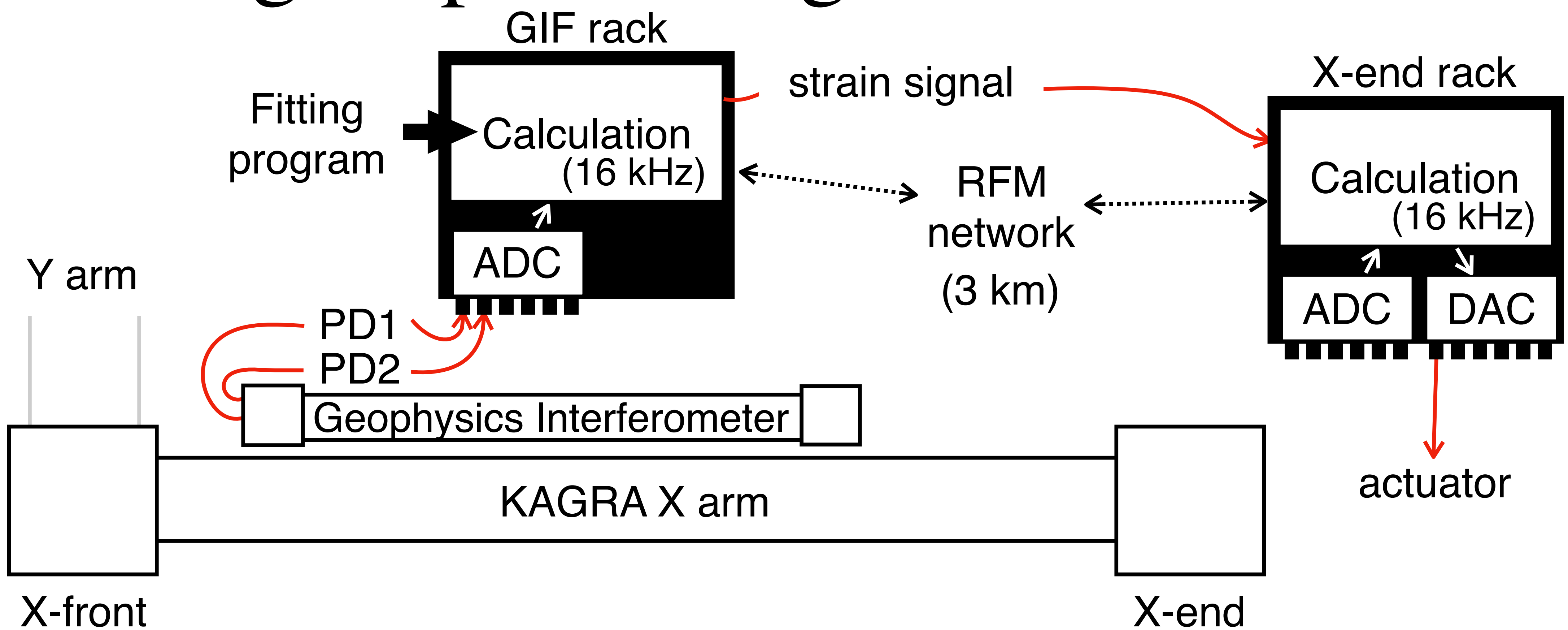
- Compensate the L_{cav} below 1 Hz
- Reduce ΔL_{cav} below 1 Hz

Method

1. Lock the platform to local ground
   $\rightarrow \Delta L_{cav} = \Delta L_{base} = \varepsilon \times 3000$
2. Feedforward $-\Delta L_{base}$ to the end actuator
   $\rightarrow \Delta L_{cav} - \Delta L_{base} \rightarrow 0$

We need realtime signal processing for feedforward control

Realtime signal processing for KAGRA



Realtime ellipse fitting (coded C language)

- 2 PD signal → strain signal
- Run every clock (1 clock = 61 usec = 1/16 kHz)

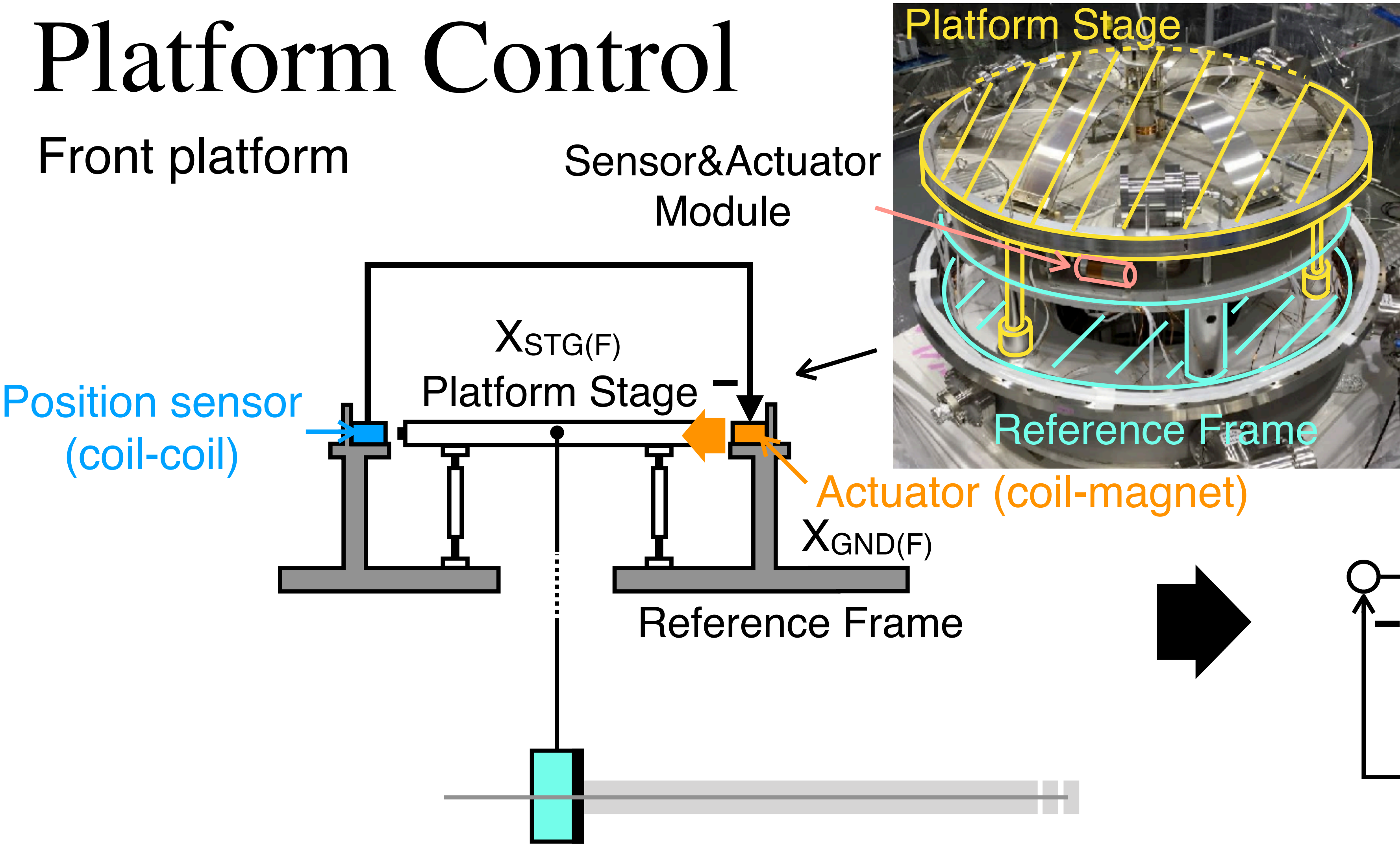
Synchronized with the other DAQ rack

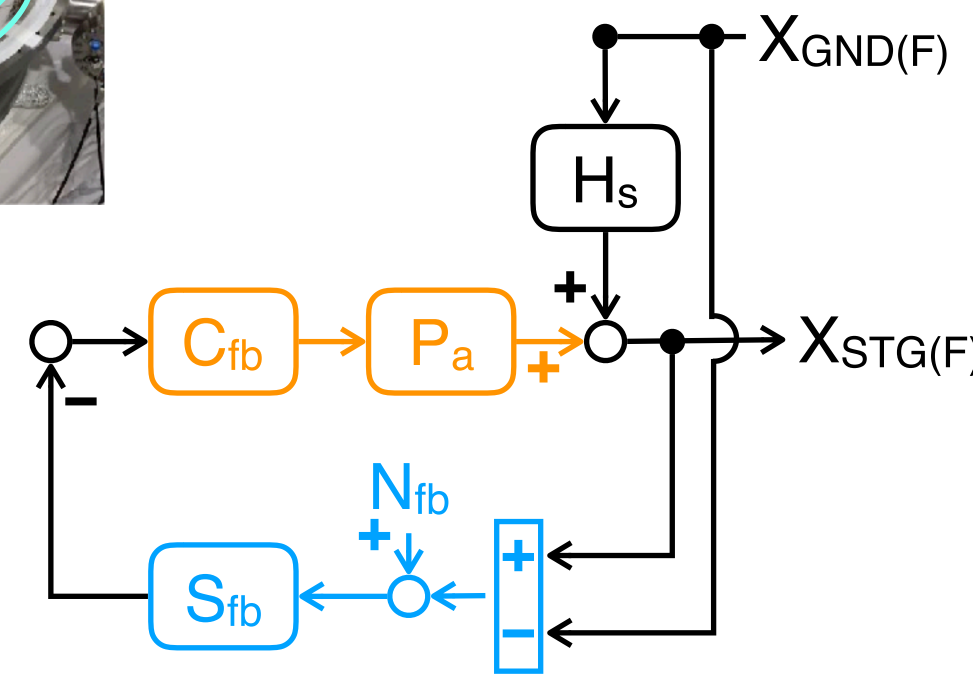
- Latency is 1 clock
- e.g. Strain signal → actuator at X-end

ADC : Analog digital converter   DAC : Digital analog converter   RFM : Reflective memory

Platform Control

Front platform





$$X_{\mathrm{STG(F)}} = \frac{G}{1+G} X_{\mathrm{GND(F)}} + \frac{1}{1+G} H_{\mathrm{s}} X_{\mathrm{GND(F)}} - \frac{G}{1+G} N_{\mathrm{fb}}$$

$$(G = C_{\mathrm{fb}} P_a S_{\mathrm{fb}})$$

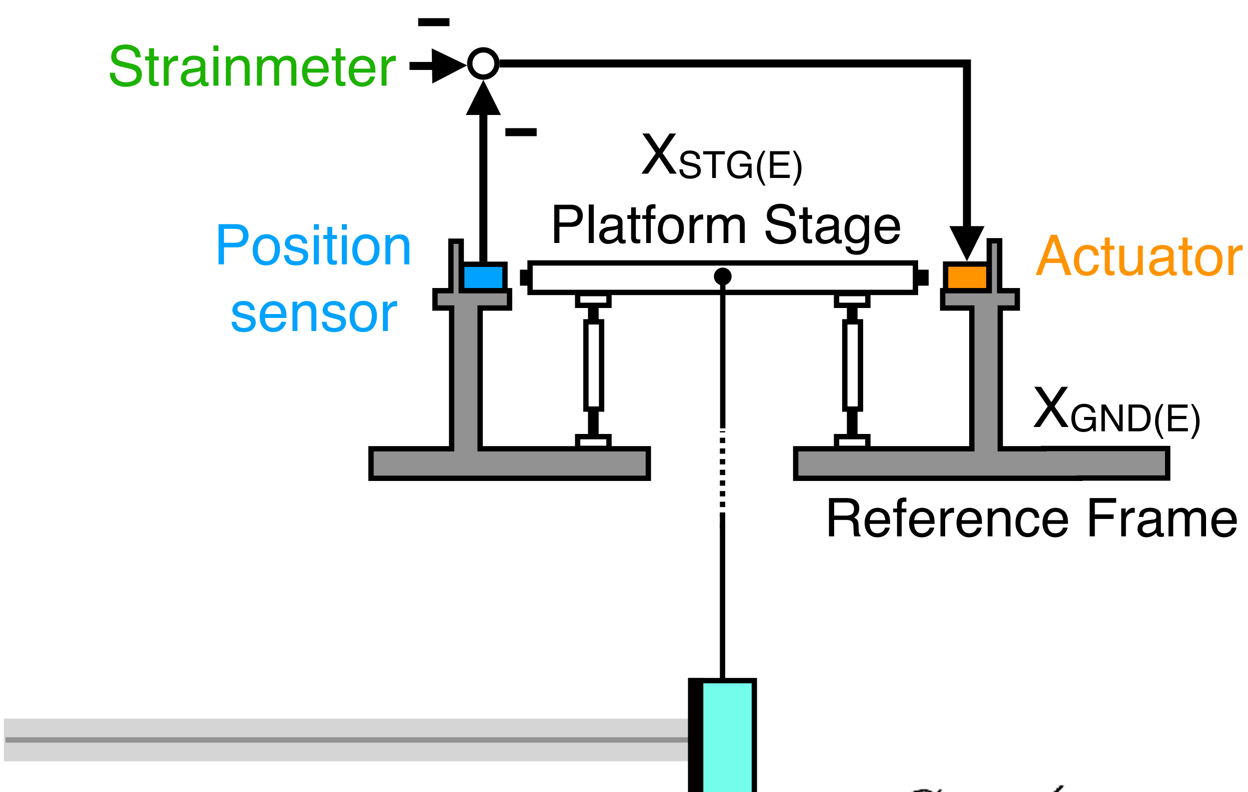
G >> 1

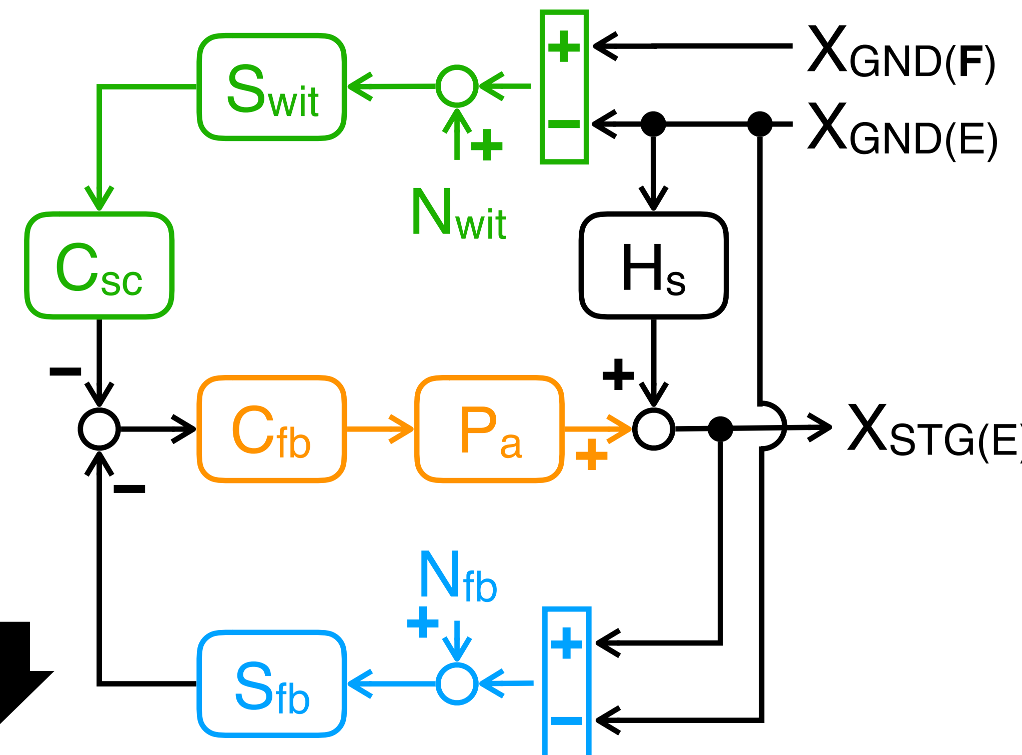
$$X_{\mathrm{STG(F)}} = X_{\mathrm{GND(F)}} - N_{\mathrm{fb}}$$

Front stage is locked to the local ground by feedback control.

Platform Control

End platform





$$X_{\mathrm{STG(E)}} = \frac{G}{1+G}\left(1 - C_{\mathrm{sc}}\frac{S_{\mathrm{wit}}}{S_{\mathrm{fb}}}\right) X_{\mathrm{GND(E)}} + \frac{G}{1+G} X_{\mathrm{GND(F)}} + \frac{1}{1+G} H_{\mathrm{s}} X_{\mathrm{GND(E)}} - \frac{G}{1+G}\left(N_{\mathrm{fb}} + C_{\mathrm{sc}}\frac{S_{\mathrm{wit}}}{S_{\mathrm{fb}}} N_{\mathrm{wit}}\right)$$

G >> 1

$$X_{\mathrm{STG(E)}} = \left(1 - C_{\mathrm{sc}}\frac{S_{\mathrm{wit}}}{S_{\mathrm{fb}}}\right) X_{\mathrm{GND(E)}} + X_{\mathrm{GND(F)}} - \left(N_{\mathrm{fb}} + C_{\mathrm{sc}}\frac{S_{\mathrm{wit}}}{S_{\mathrm{fb}}} N_{\mathrm{wit}}\right)$$

$$C_{\mathrm{sc}} = \frac{S_{\mathrm{fb}}}{S_{\mathrm{wit}}}$$

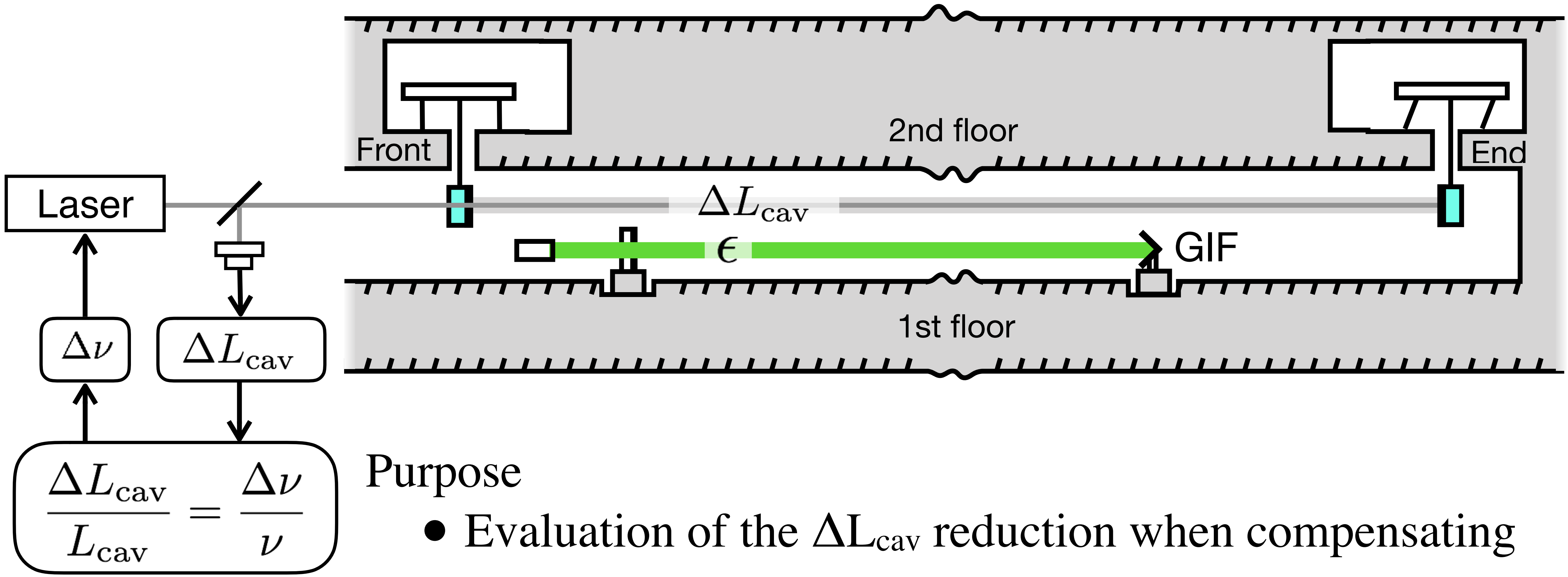
$$X_{\mathrm{STG(E)}} = X_{\mathrm{GND(F)}} - N_{\mathrm{fb}} - N_{\mathrm{wit}}$$

$$\Delta L_{\mathrm{cavity}} = X_{\mathrm{STG(F)}} - X_{\mathrm{STG(E)}} = -N_{\mathrm{fb(F)}} + N_{\mathrm{fb(E)}} + N_{\mathrm{wit}}$$

ΔL_{cav} can be reduced to the sensor noise level.

Contents

Setup for Demonstration



Purpose

- Evaluation of the ΔL_{cav} reduction when compensating

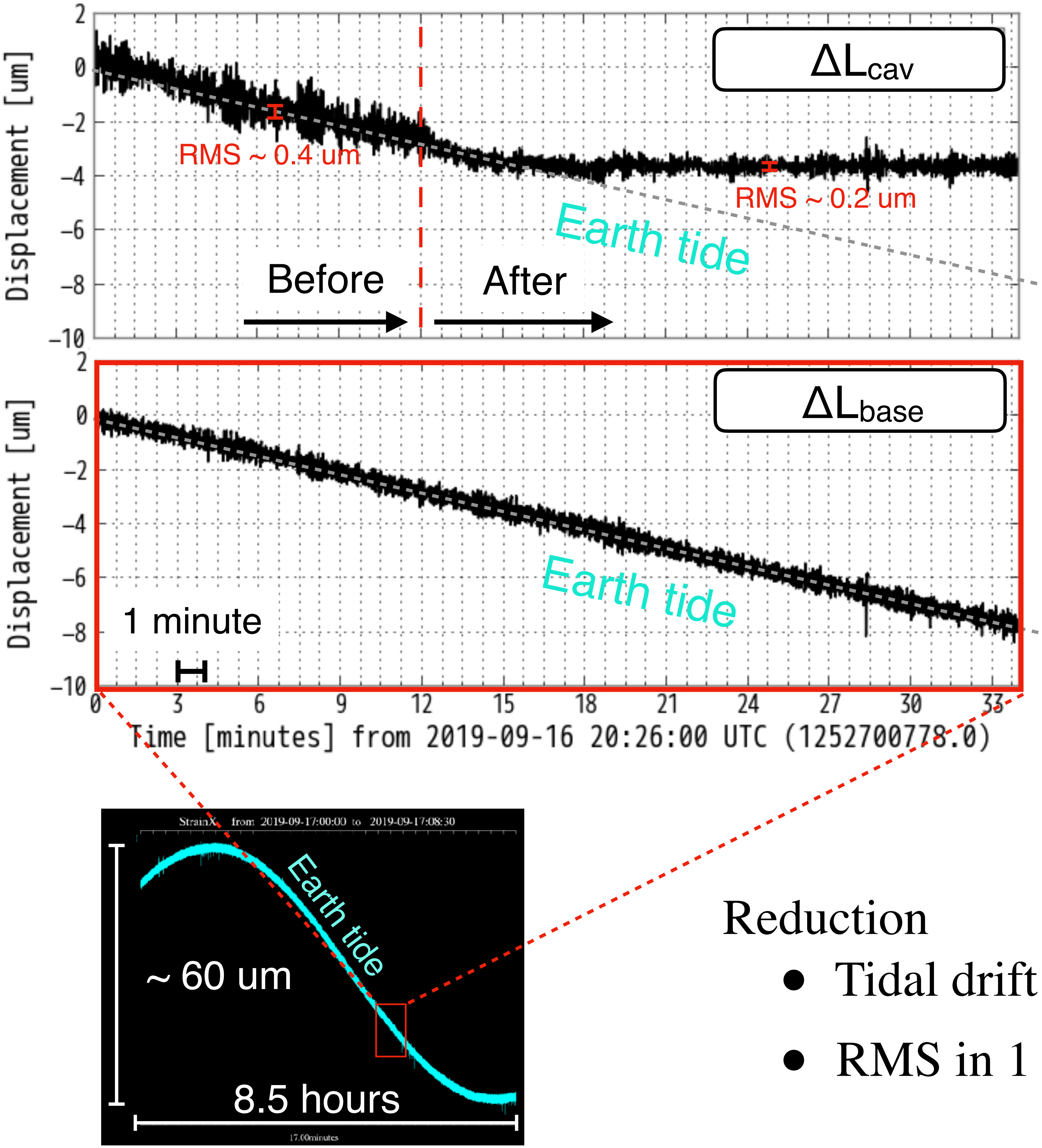
ΔL_{cav} measurement

- Lock the laser frequency
- $\Delta L_{cav} \propto$ feedback signal ($\Delta\nu$)

ΔL_{base} measurement

- Use strainmeter
- $\Delta L_{base} = \varepsilon \times 3000$

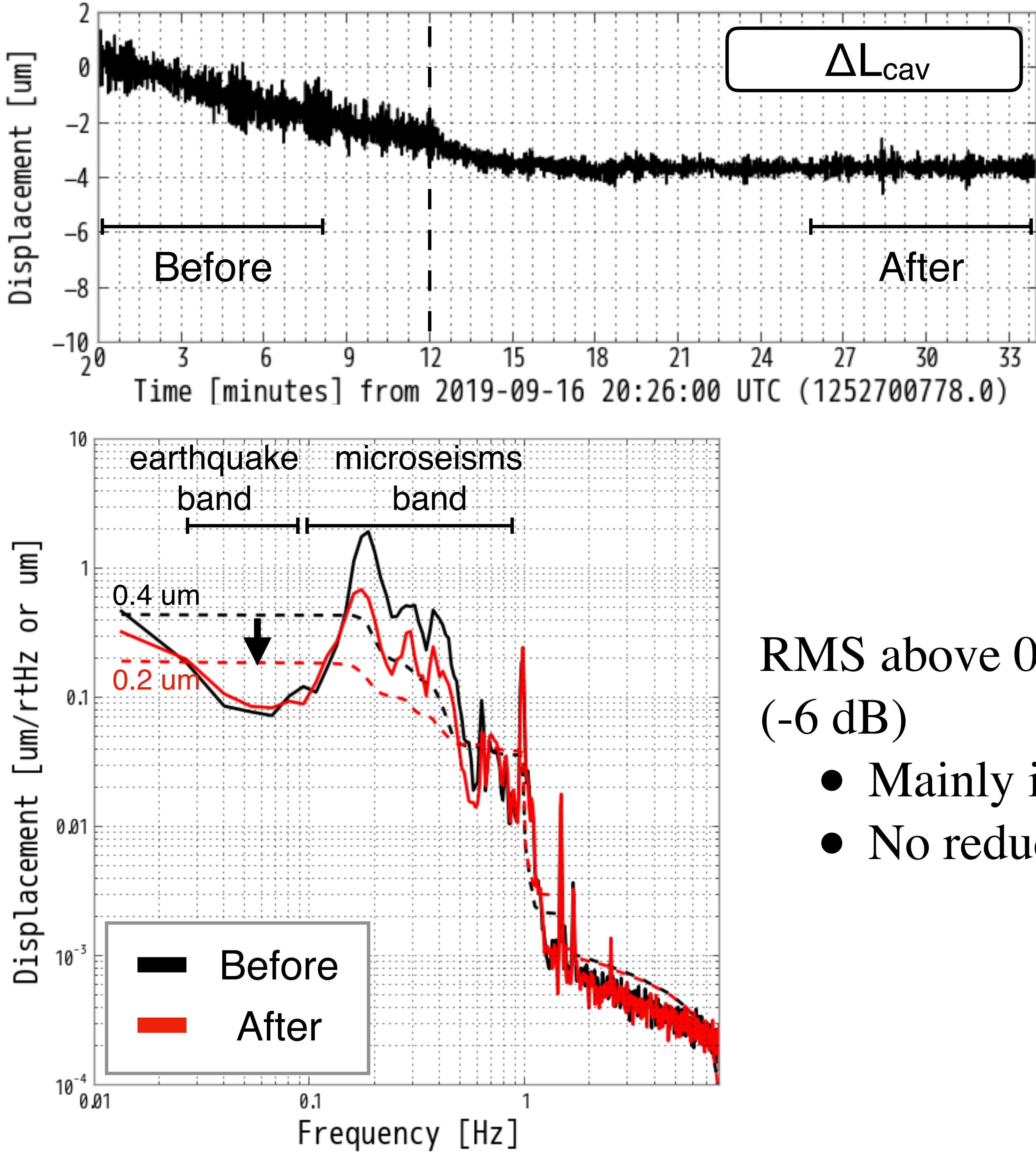
Results : Time domain



Reduction

- Tidal drift
- RMS in 1 minutes

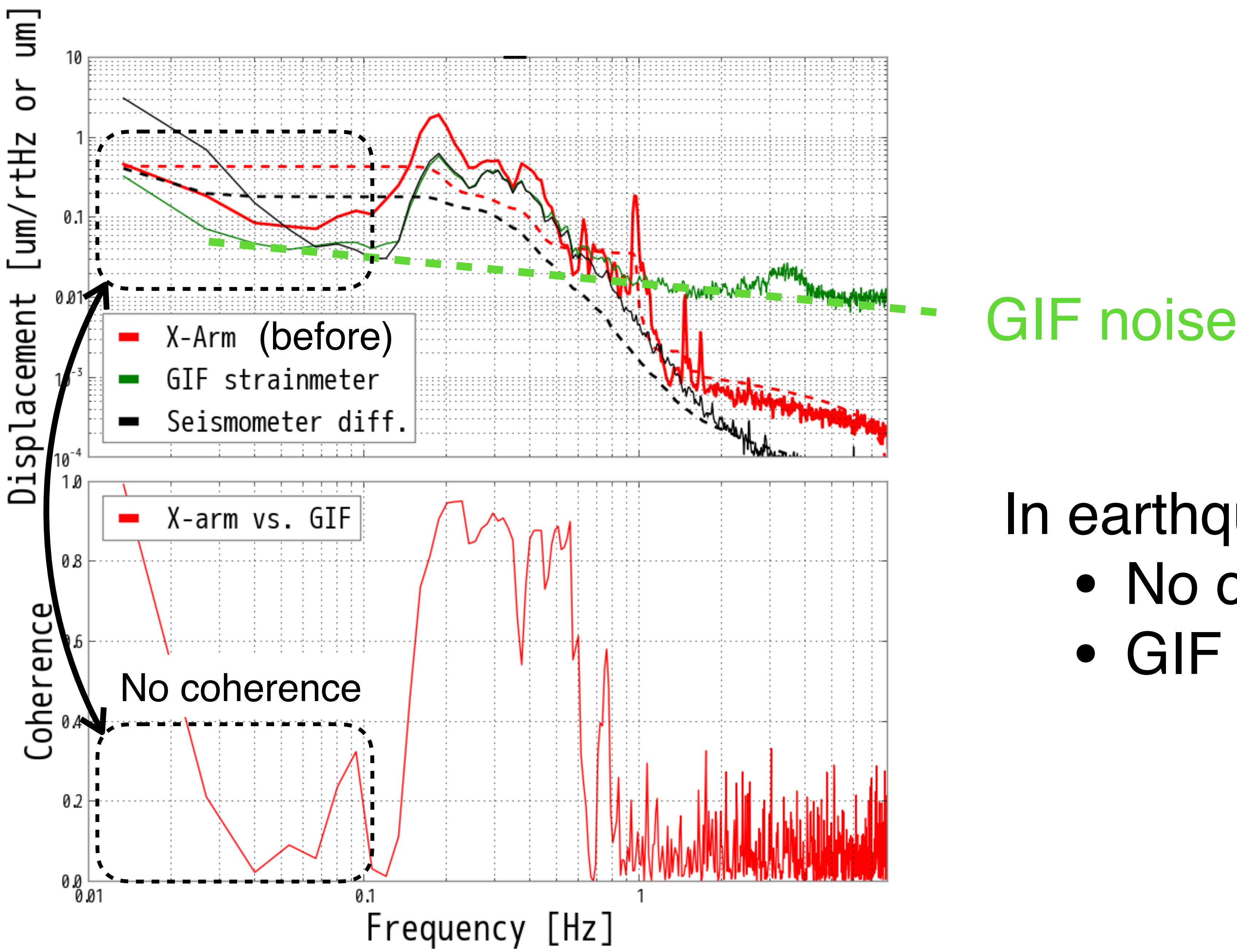
Results : Frequency domain



RMS above 0.01 Hz is reduced by 1/2 (-6 dB)

- Mainly in the microseismic band
- No reduction in earthquake band

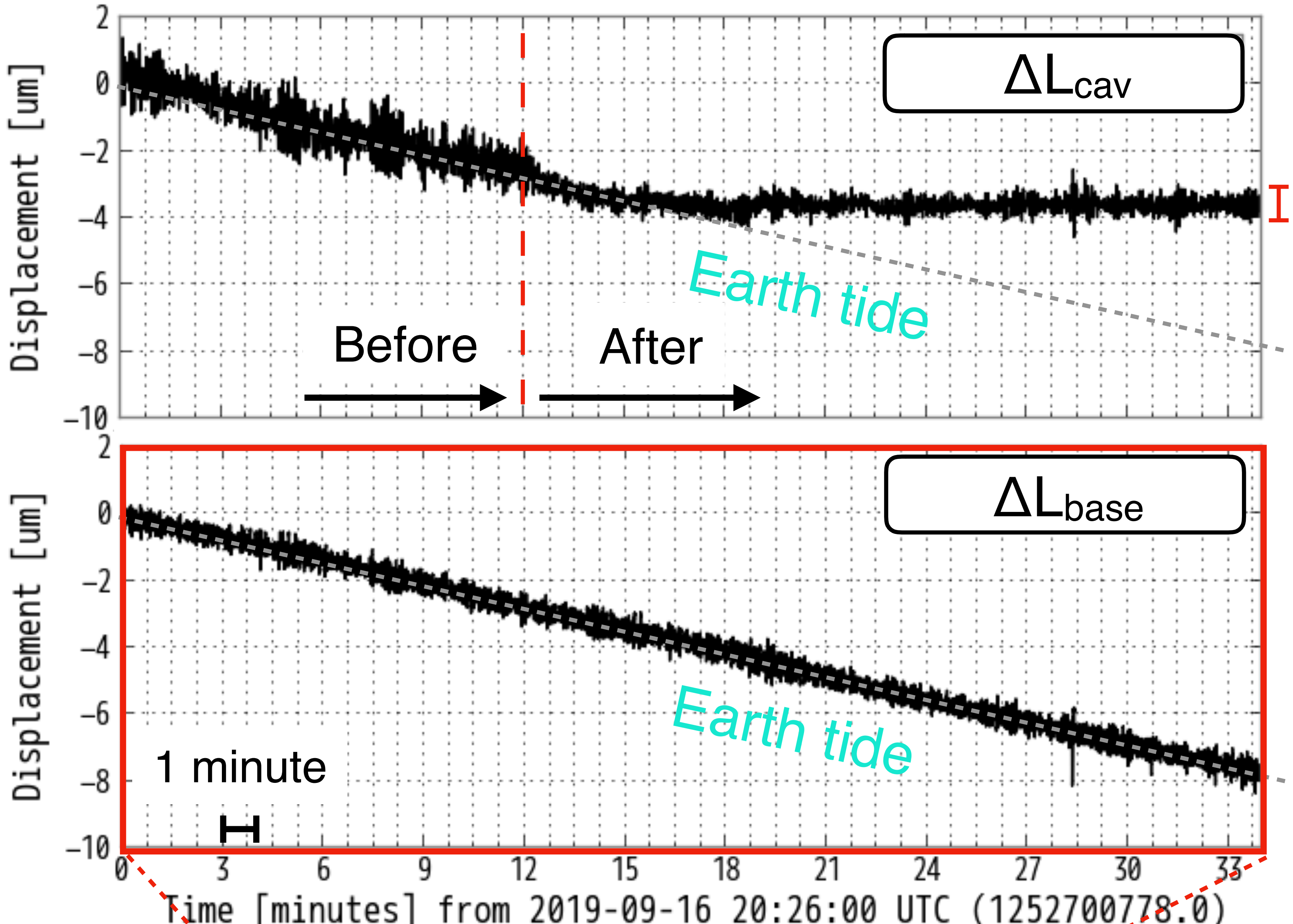
Discussion : Earthquake band

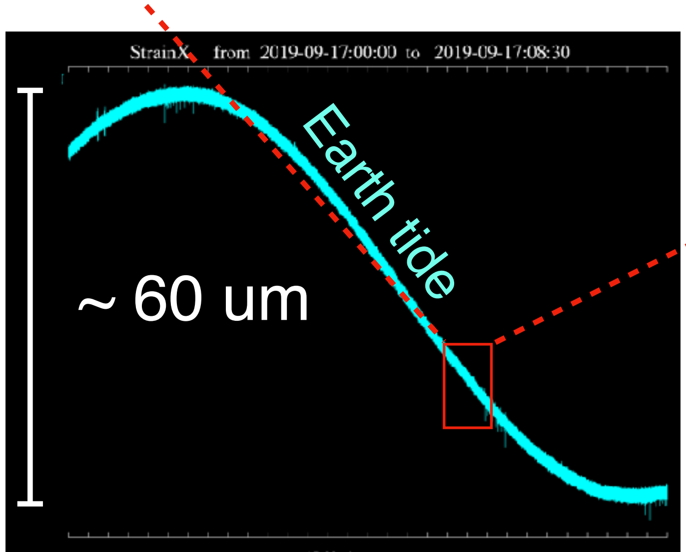


In earthquake band,
- No coherence
- GIF noise limit

There are no reduction because of GIF noise.

Discussion : Reduction rate





Reduction rate should be less than -6 dB.

RMS in 20 minutes < 1 um

↓

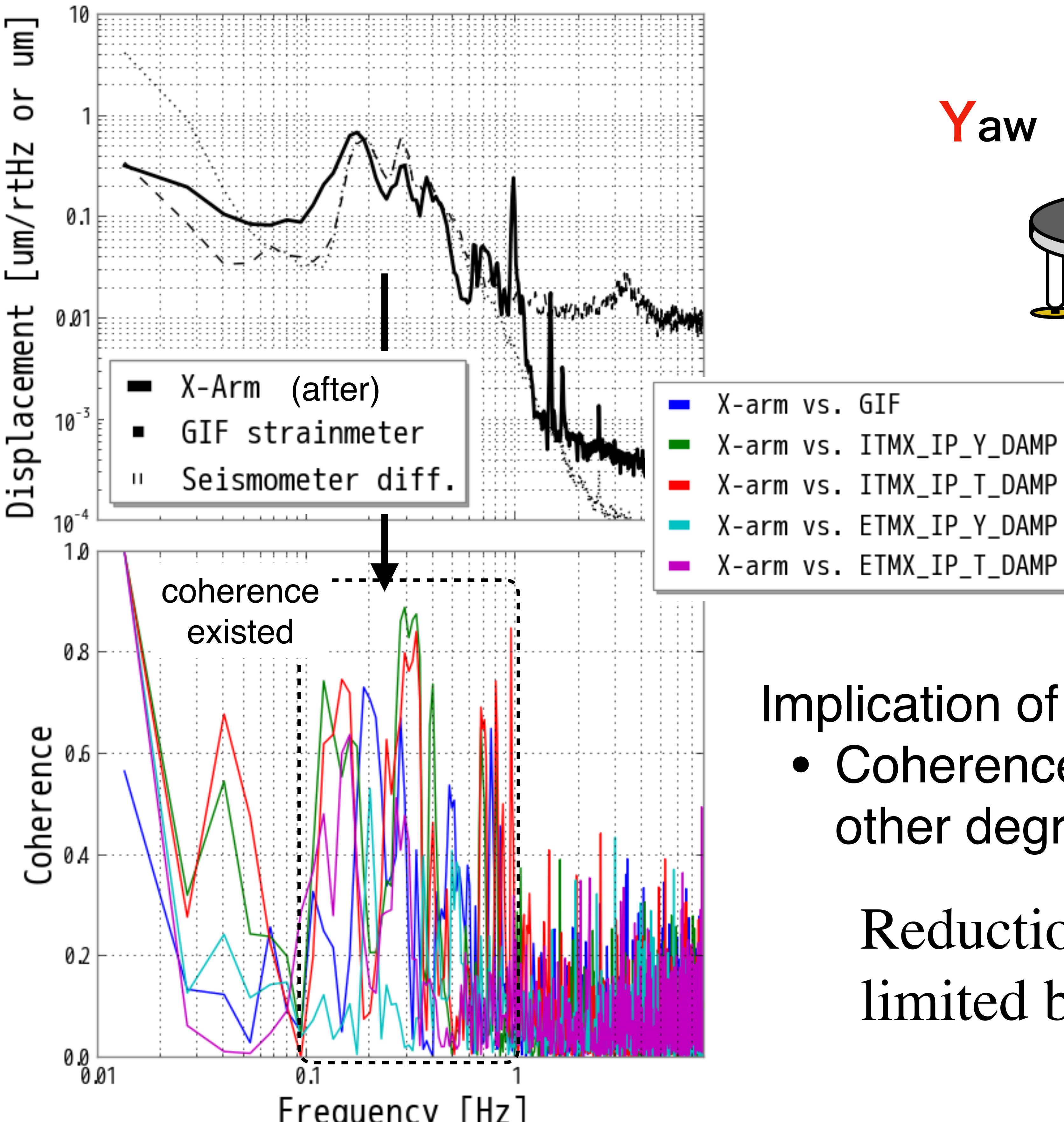
Assuming RMS in tidal band = 1 um

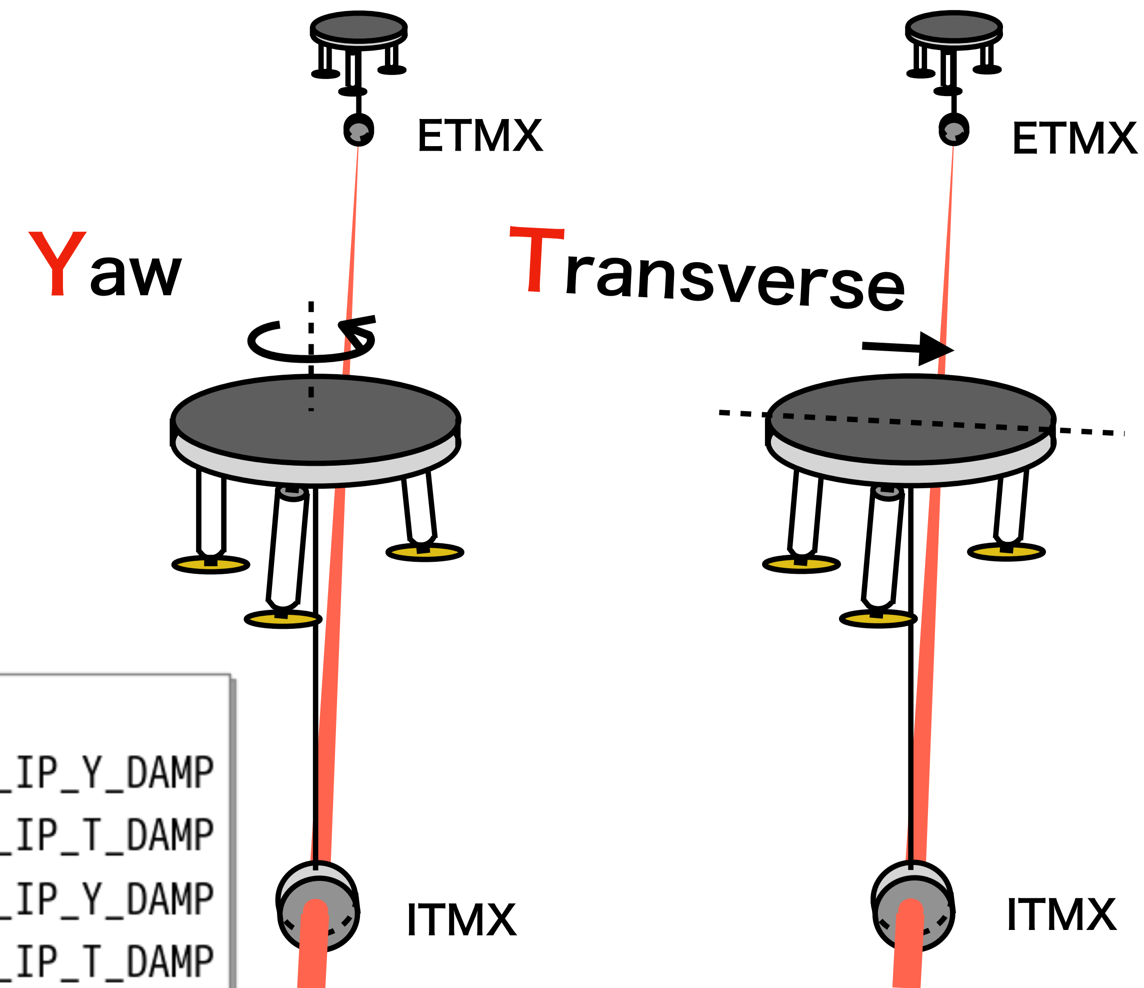
↓

Expected reduction rate ~ 1/60 (-35 dB)

Reduction rate in microseismic band might be limited by some reason.

Discussion : Microseismic band





Implication of signal coupling

- Coherence between X-arm and other degrees of freedoms (DOFs).

Reduction of -6 dB might be limited by the couplings

Contents

Conclusion

- Duty cycle is limited by low-frequency seismic noises
  - Microseismic noise (0.1 - 1 Hz)
  - Large earthquake (0.03 - 100 mHz)
  - Earth tides (1 day)

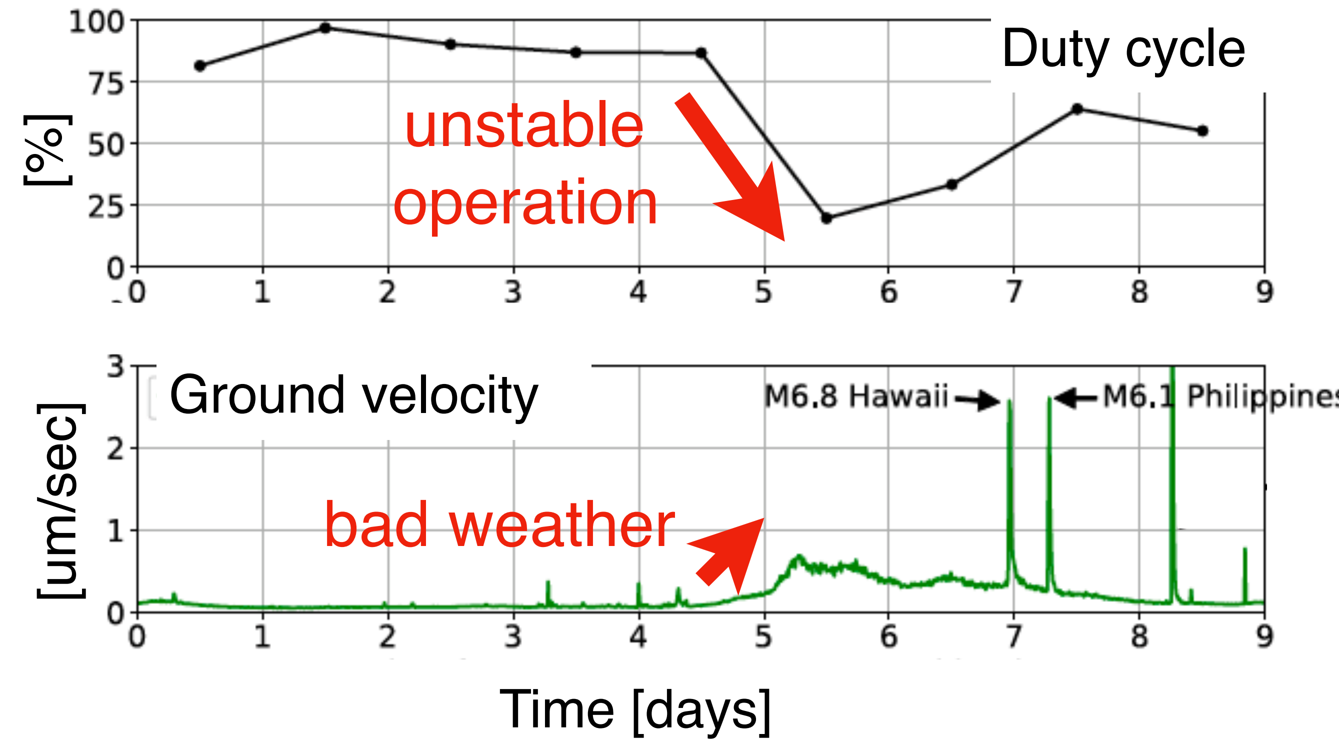
- I designed the baseline compensation system and demonstrate its performance by using X-arm cavity of KAGRA.

- As a result, there are reduction owing to the compensation
  - -6 dB reduction in microseismic band
  - No obvious reduction in earthquake band
  - More than -35 dB reduction in earth tide band

- This is the first demonstration of the baseline compensation on the km-scale GW detector in the world.

Future Prospects

Reduction in microseismic band will improve the unstable operation of KAGRA due to bad weather. →



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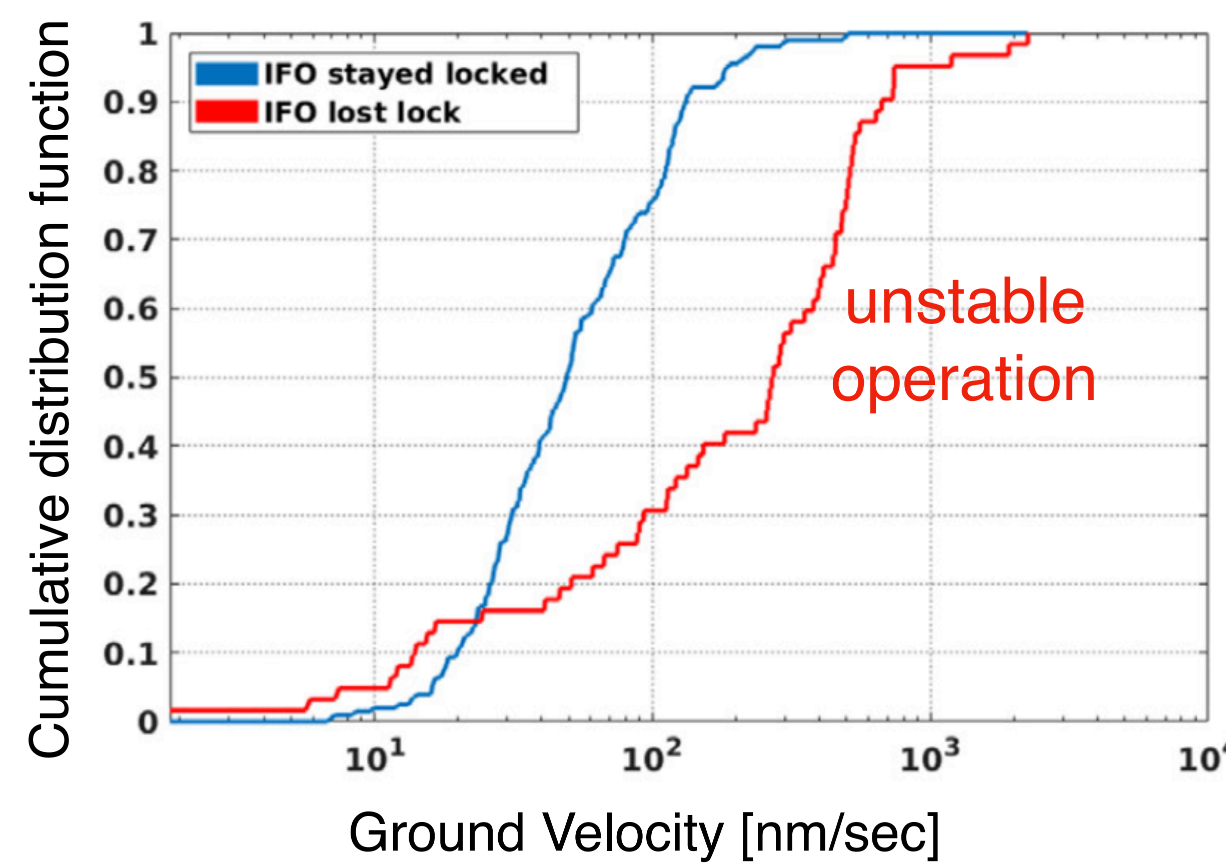
Reduction in earthquake band will improve the duty cycle of all GW detectors.



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Reduction in earth tide will relax the hierarchical feedback control, and GW detector will lock the cavity easily. This advantage will improve the duty cycle of all detectors.

Future Prospects

- When the baseline compensation system is installed in the all of GW detectors, the network duty cycle will improve.
- Longer duty cycle will enhance the GW astronomy.
- GW astronomy will discover new astrophysical phenomena, and provide some knowledge of the universe to us.