Low-frequency ground deformation observed by the geophysics interferometer (GIF) in the KAGRA tunnel

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1. Seismic/geodetic observation using laser strainmeters
2. Long-baseline laser strainmeter (GIF) in KAGRA
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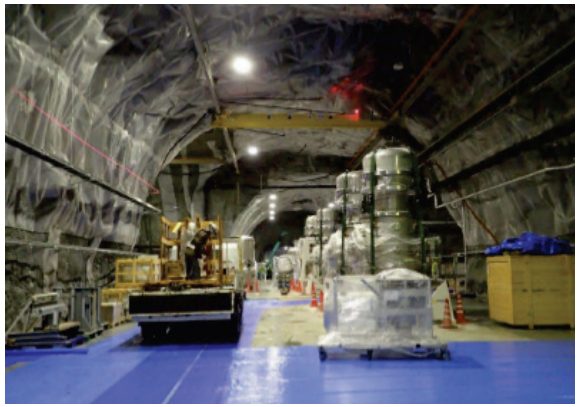
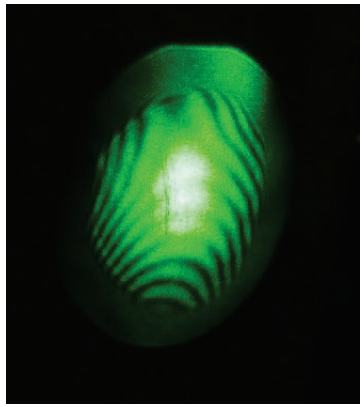
4. Demonstration of the arm-length control of KAGRA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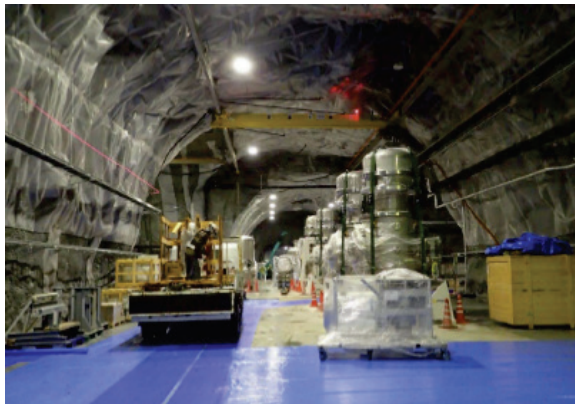
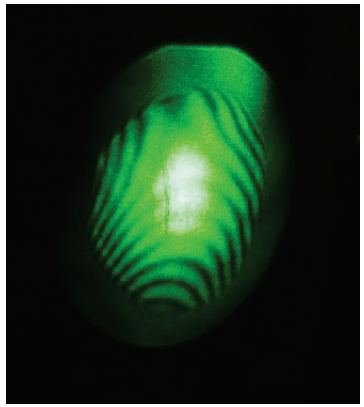
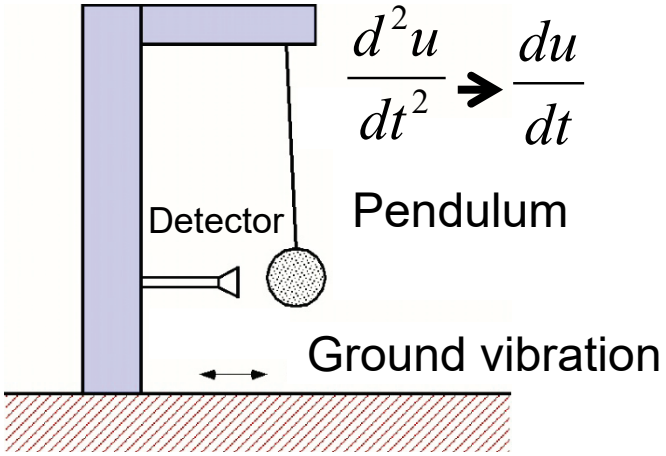




Seismometer and Strainmeter

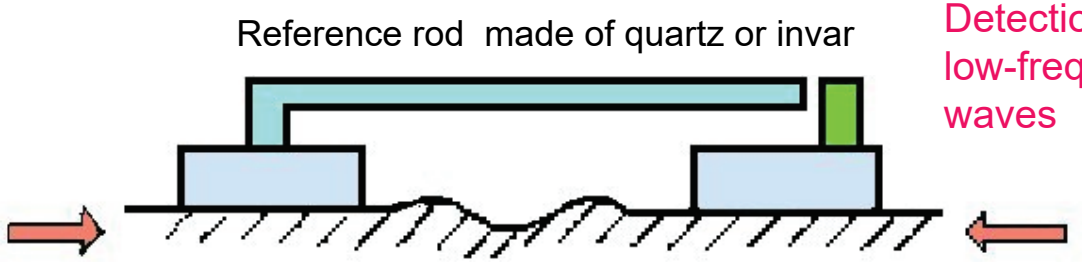


$$\frac{d^2u}{dt^2} \rightarrow \frac{du}{dt}$$

Seismometer
--- Inertial sensor with cut-off f_c

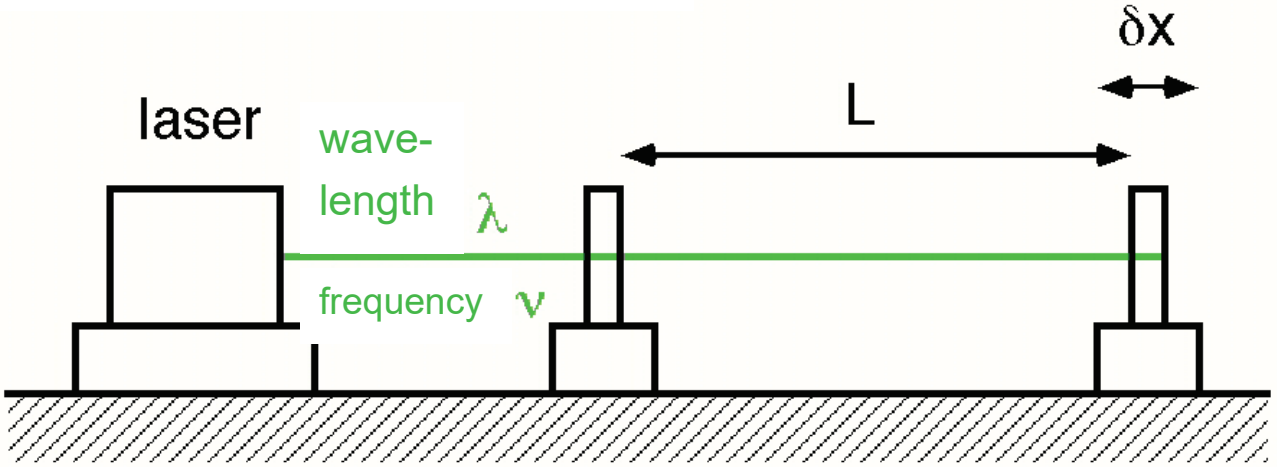
$$\frac{u(x+dx)-u(x)}{L} \cong \frac{\partial u}{\partial x}$$

Strainmeter
--- Measuring distance



Detection of low-frequency waves

Laser strainmeter (Vali et al., 1965)



optical phase : $\phi=2k(L+\delta x)$ $(k=2\pi/\lambda)$

strain : $\varepsilon = \delta x/L = \delta\nu/\nu$

Laser frequency stability

~10^{-13}

Advantages of laser strainmeters ----- very broadband observation

Rapid response → Strain seismometer

Long baseline (~1000m) → Accuracy and Broadband

Low drift (use of highly stabilized laser) → Crustal movement sensor

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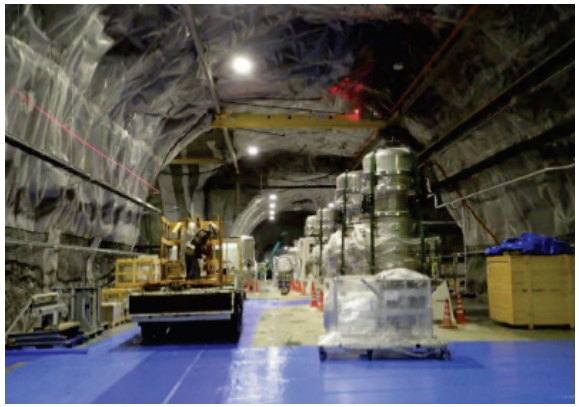
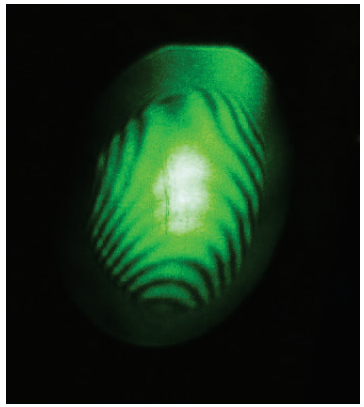
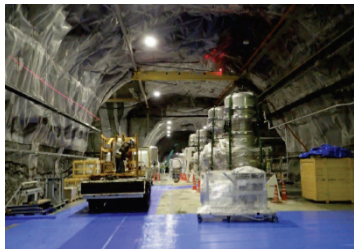
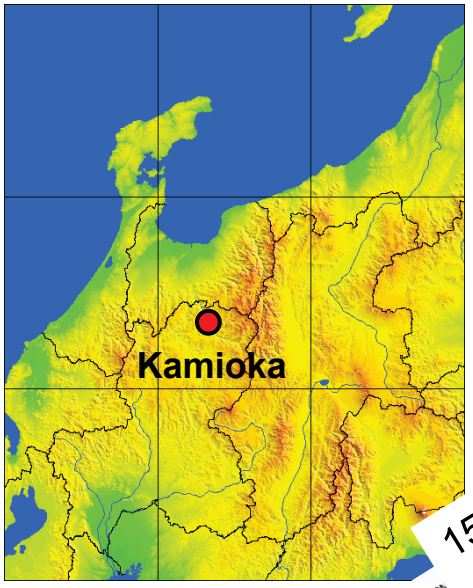
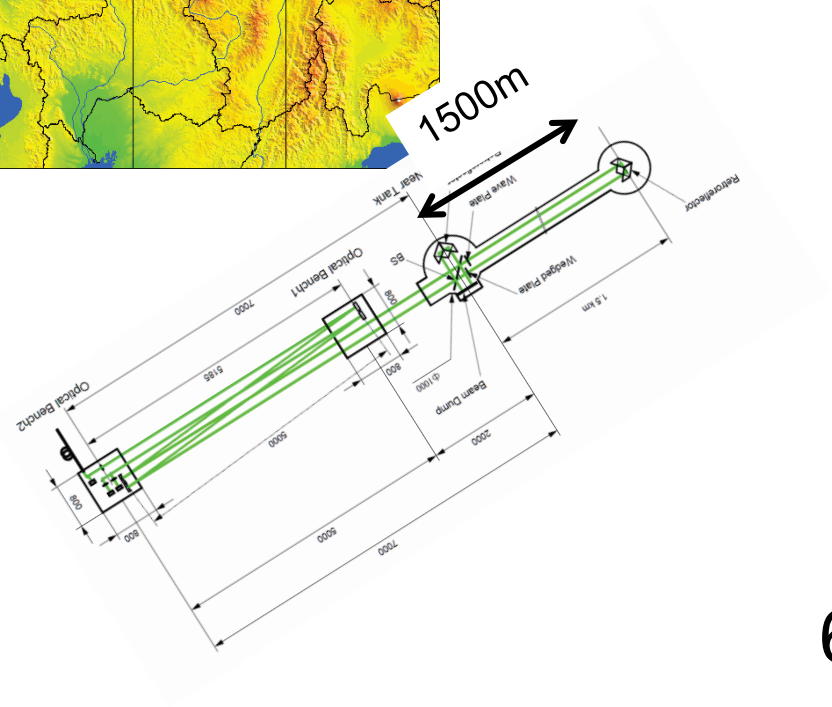



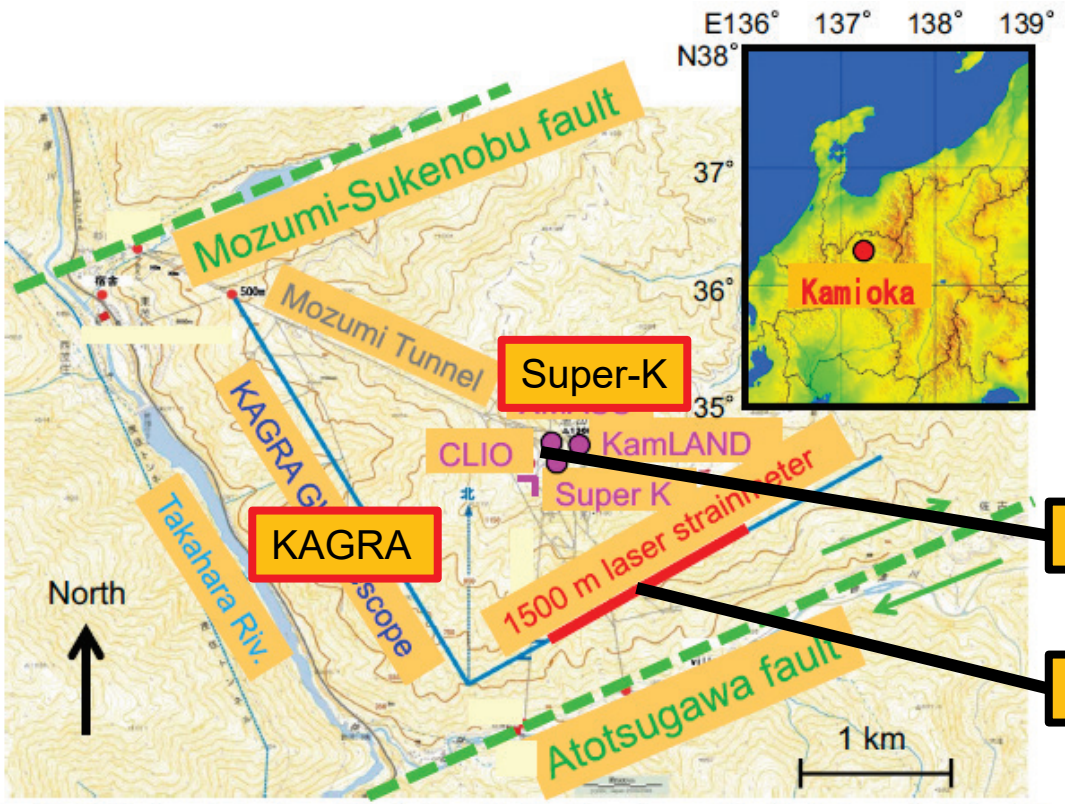

Construction of a 1500-m laser strainmeter in the KAGRA tunnel

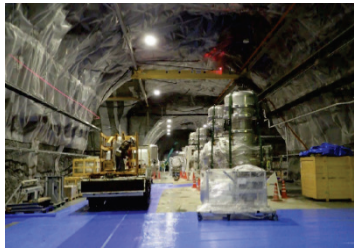




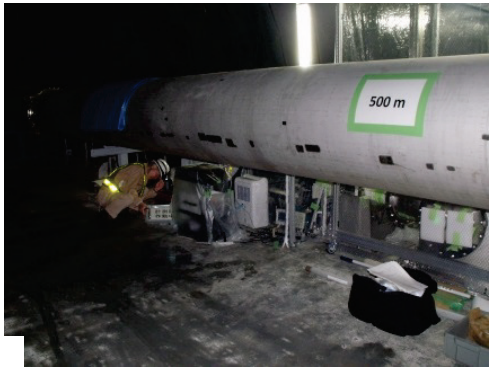


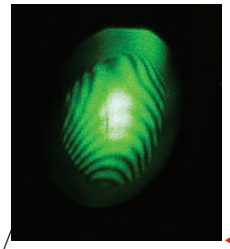
KAGRA baselines and fault locations (Cosmic Ray Research Institute, Univ. of Tokyo)





Optical configuration of GIF-X





1500m

5m

Retroreflector

Wedged Plate

End Tank

Wave Plate

BS

Retroreflector

Near Tank

Optical Bench1

Cover for Input-Output Optics

Optical Bench2

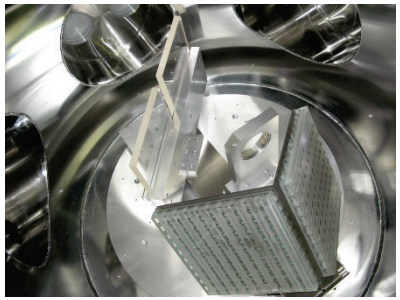
Input path

Stabilized laser

End reflector

Front reflector

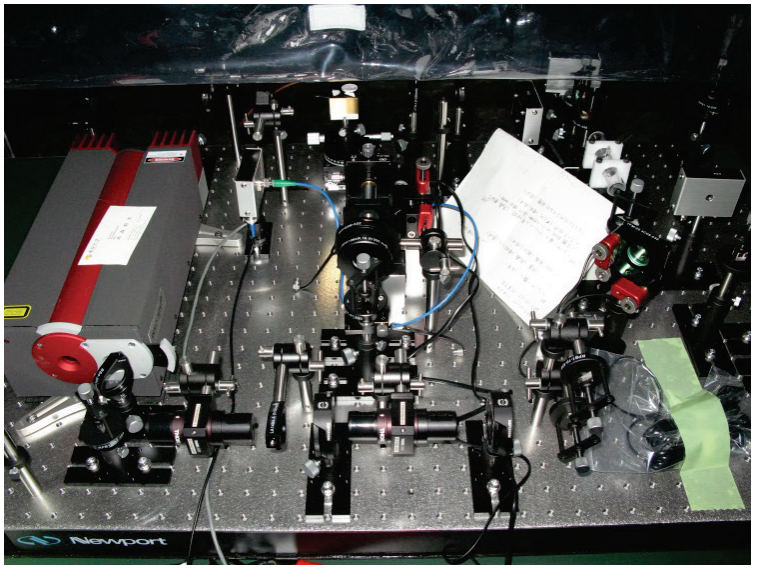
Laser

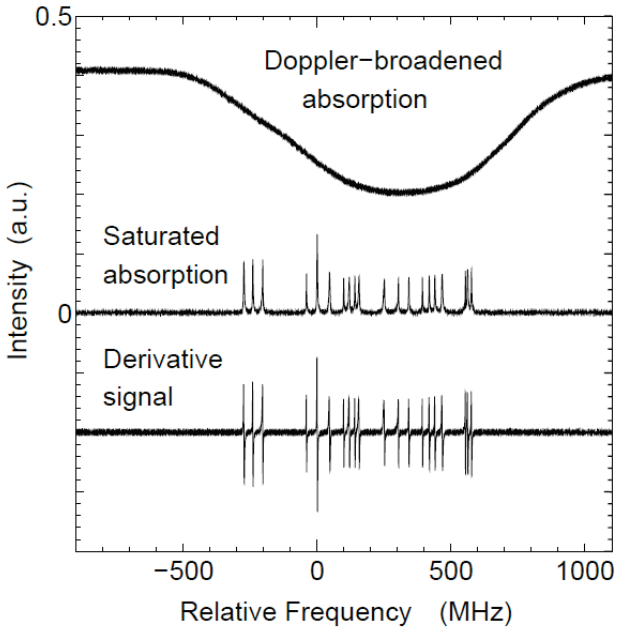


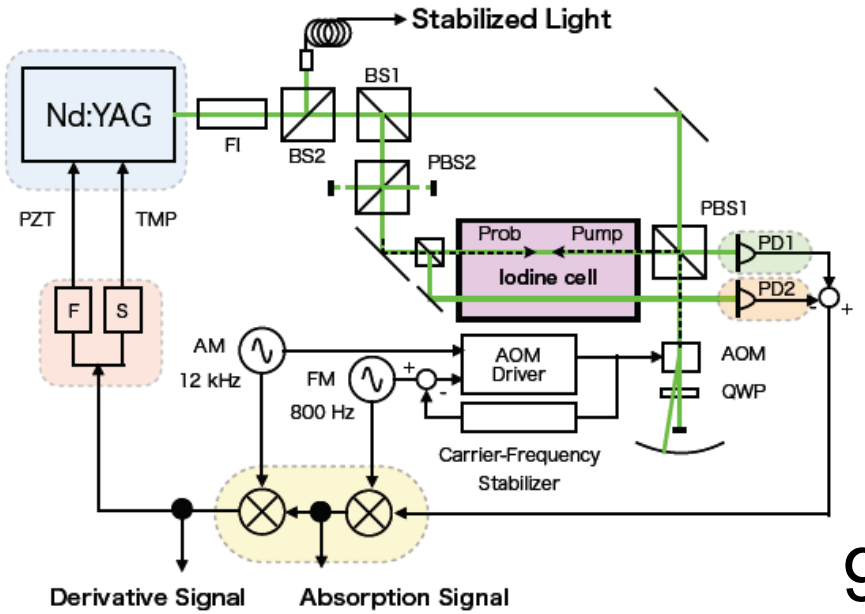
I_2 stabilized laser

Locked to iodine Doppler-free absorption (532nm)

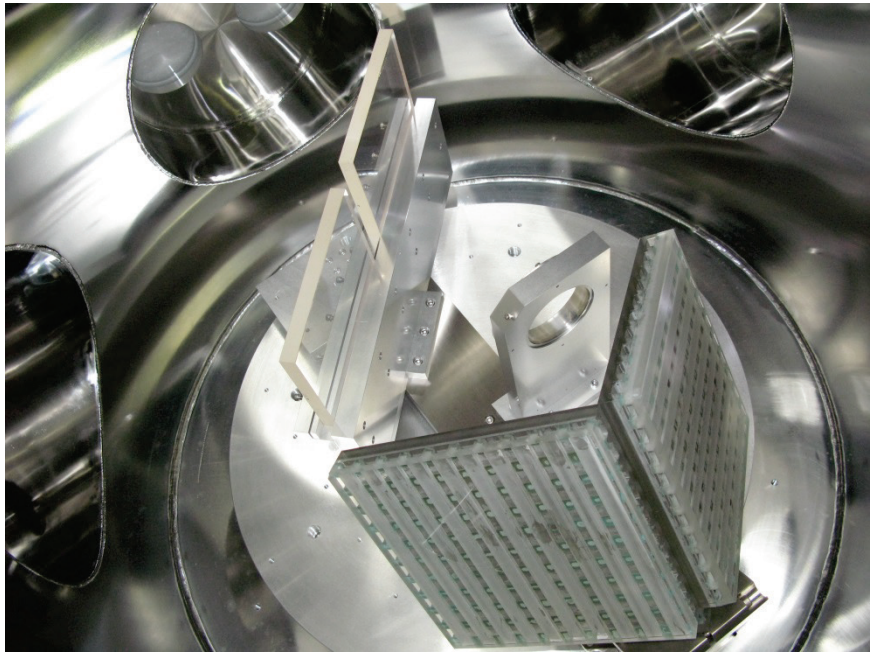
Stability of ~10^{-13} in Allan variance estimation



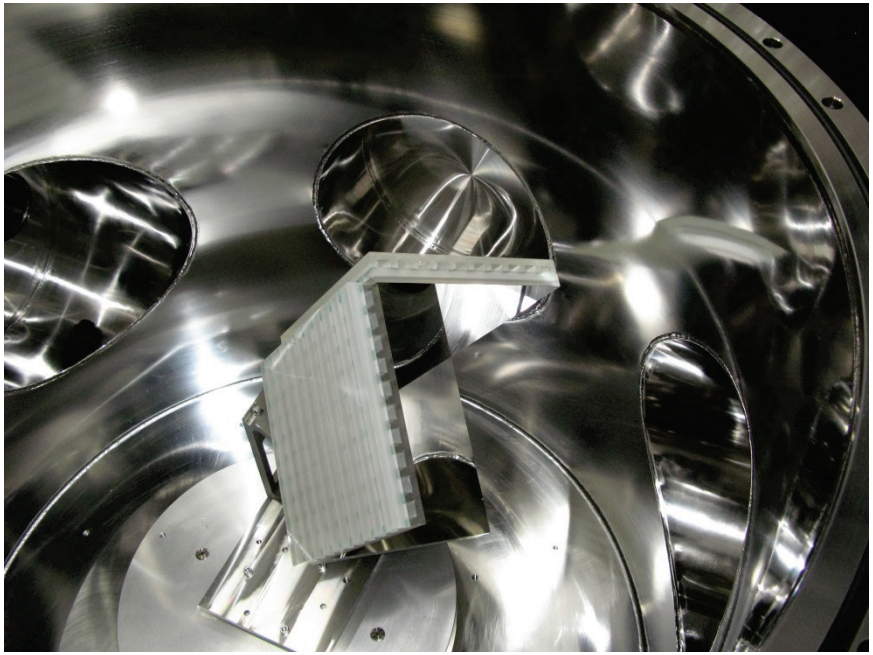




Beam splitters and retroreflectors (nominal aperture diameter: 15inch=38cm)

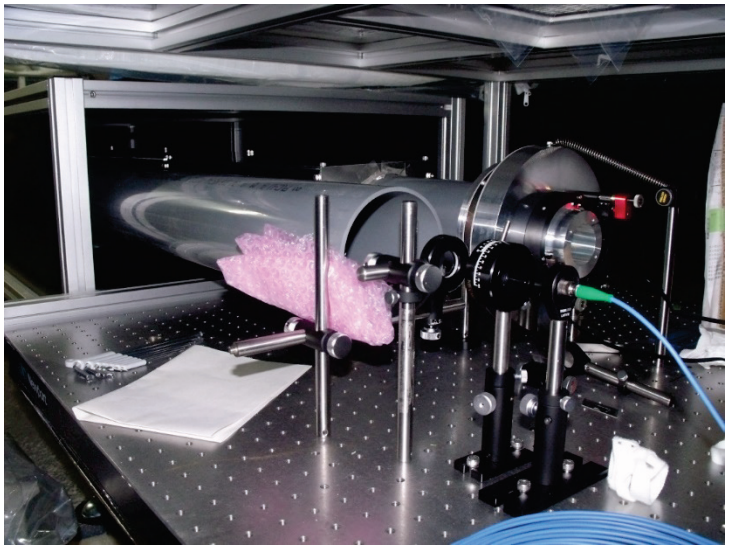


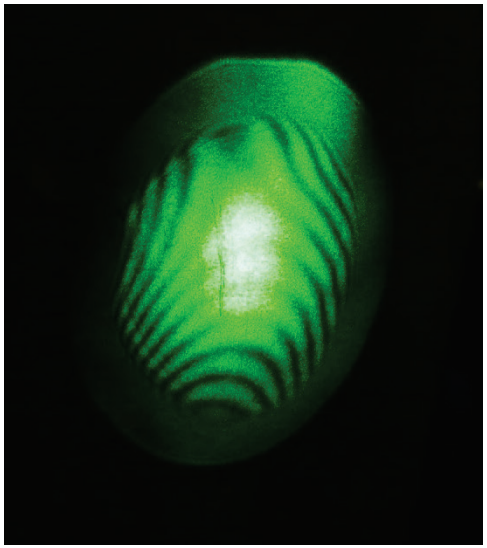
Optics in front tank

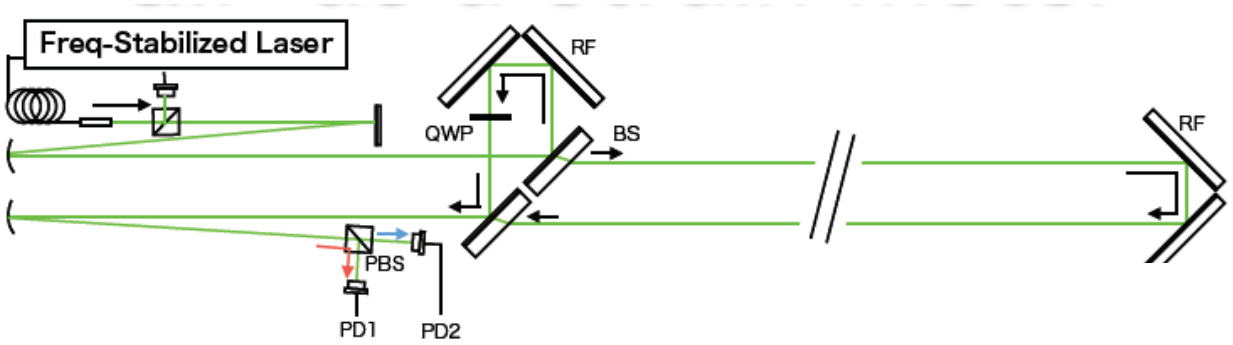


Retroreflector in end tank

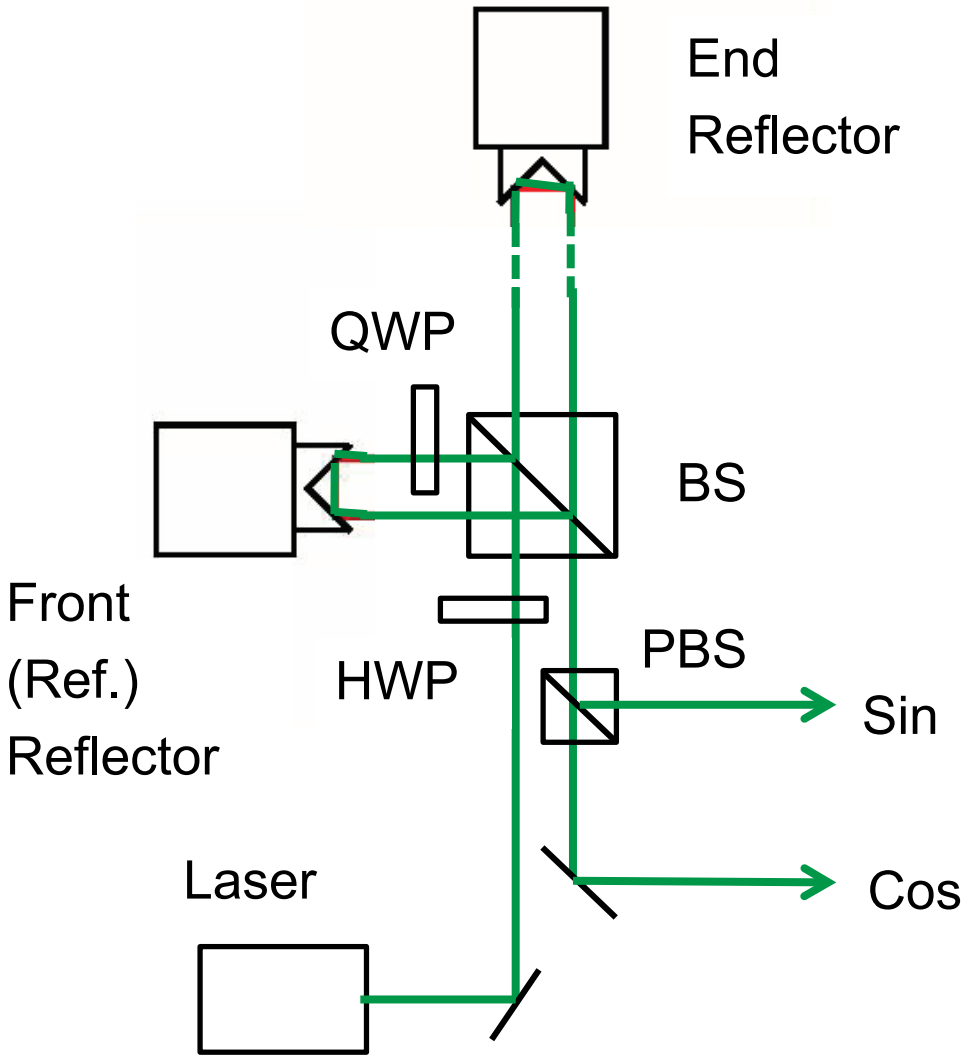
Input optics (left) and interferometer fringe (right).

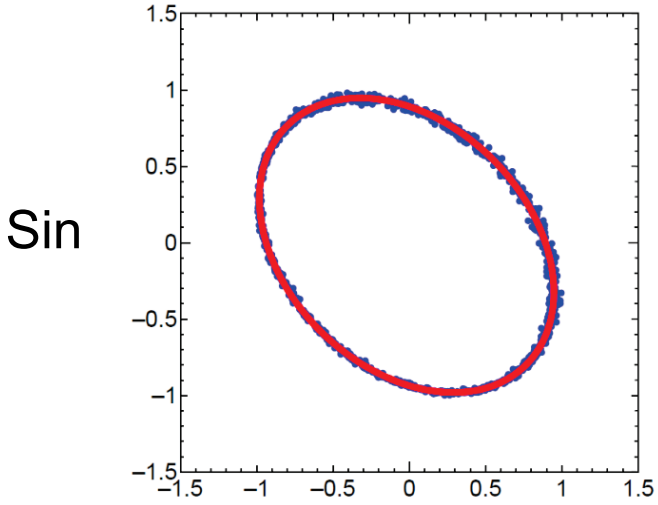


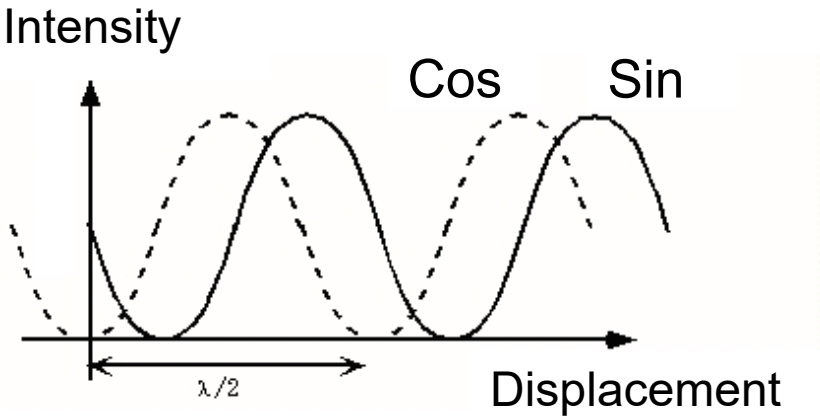




Quadrature Interferometer (no feedback to mirrors)







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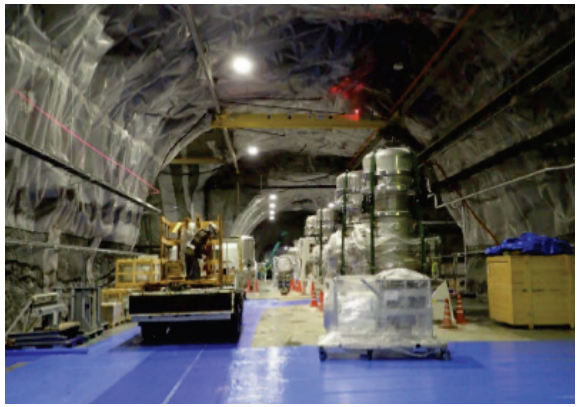
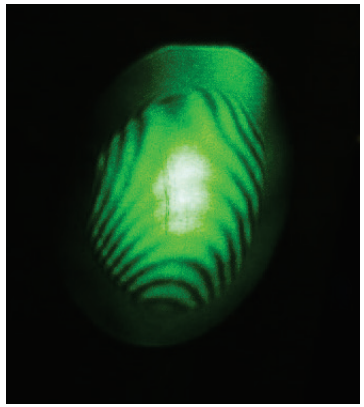
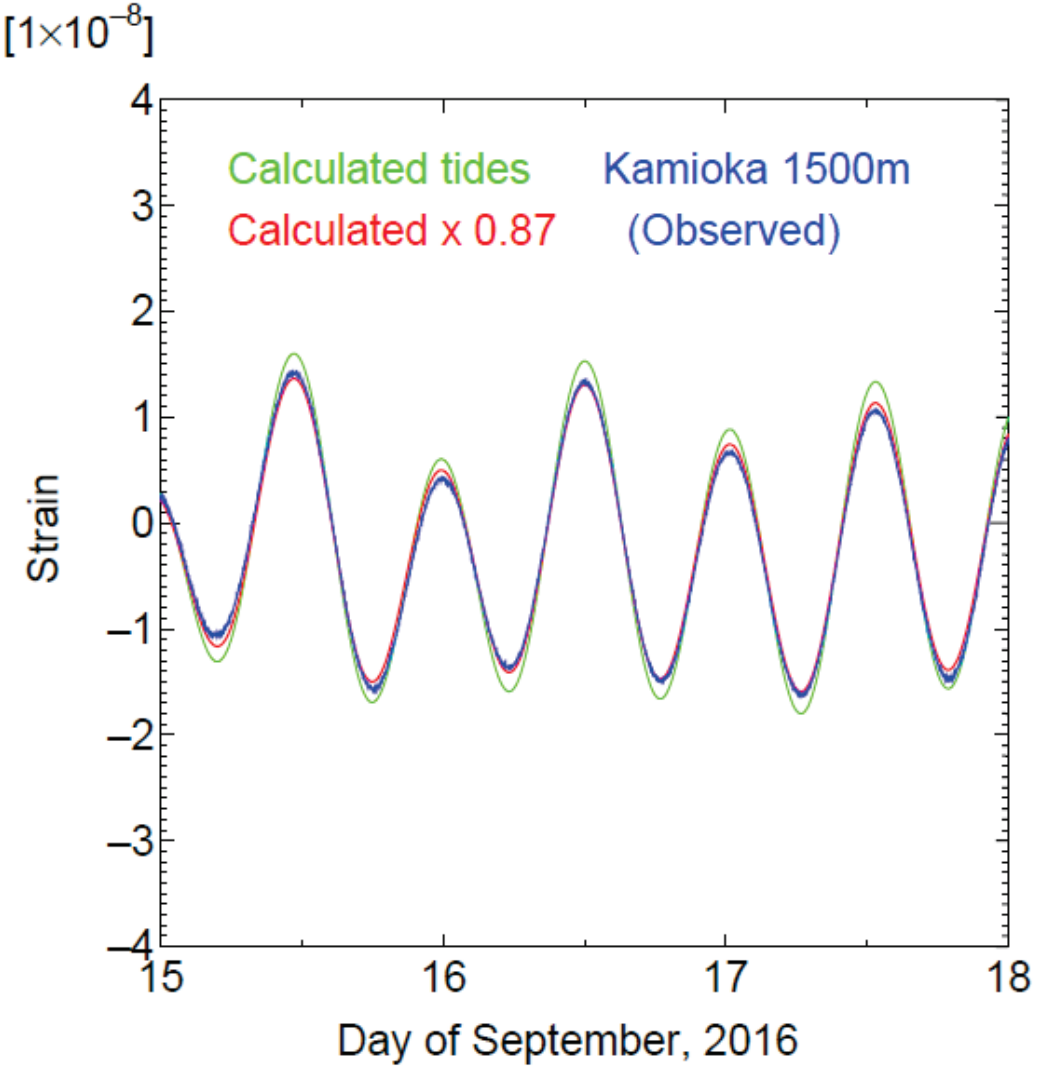



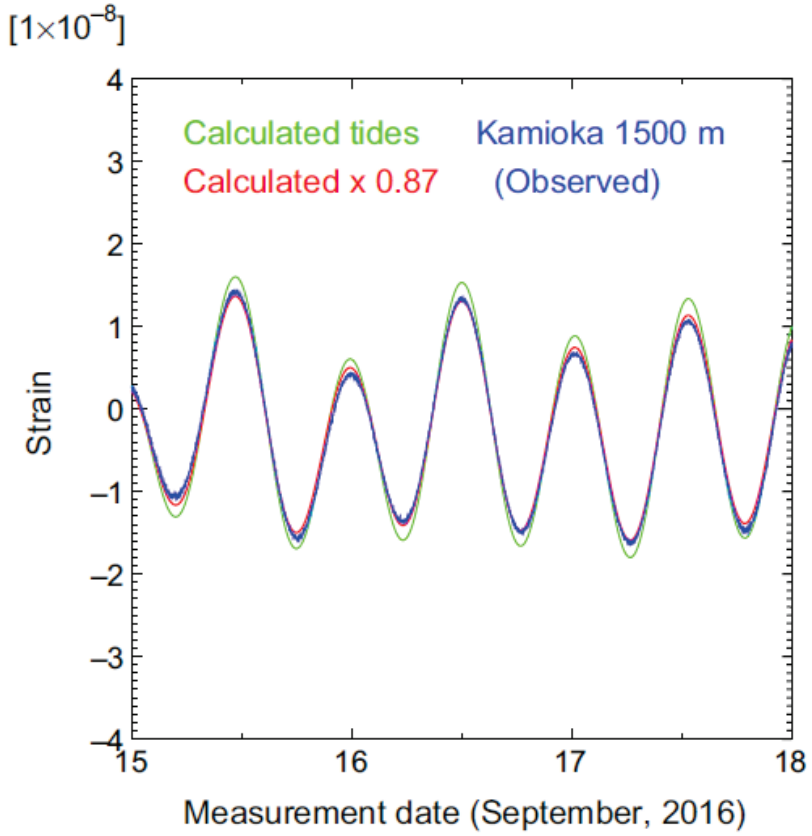

Earth tides --- ~3x10^{-8} in strain

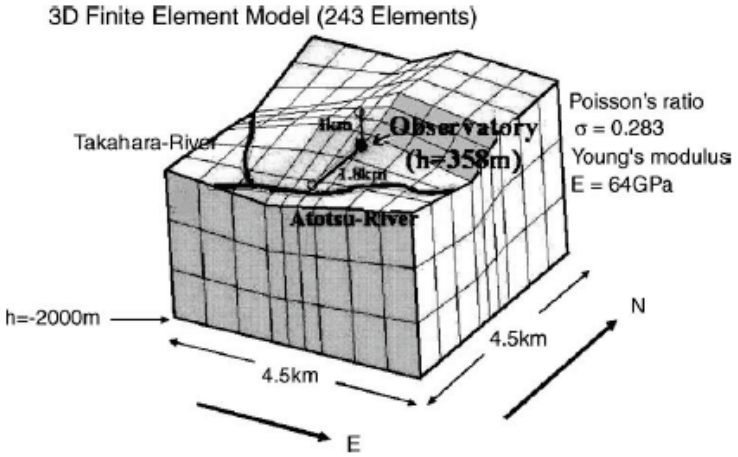
Observed amplitude --- 0.87 of theoretical calc.

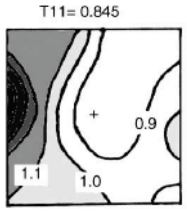
Earth tides are reduced by topographic effect



Observed Earth tides (left) and Topographic effects of underground site







$$\varepsilon_{NS} = 0.901 e_{NS} + 0.006 e_{EW} + 0.009 e_{NS-EW}$$

$$\varepsilon_{EW} = -0.011 e_{NS} + 0.845 e_{EW} + 0.025 e_{NS-EW}$$

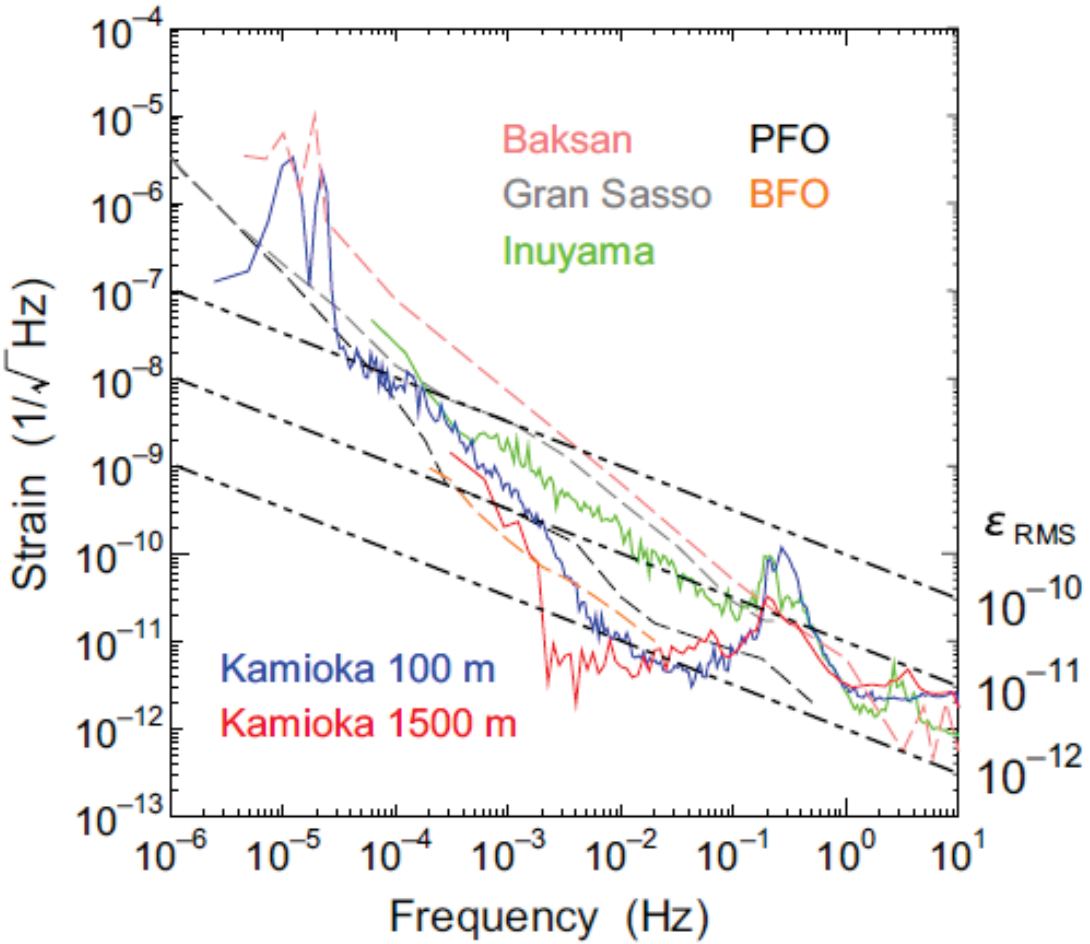
Reduction of tidal amplitude due to topography, 80-90% (Takemoto, 2006)

Strain spectra

Lowest background, especially at around (1-10) mHz

Capable of detecting pico-strain level.

Araya et al., EPS, 2017.



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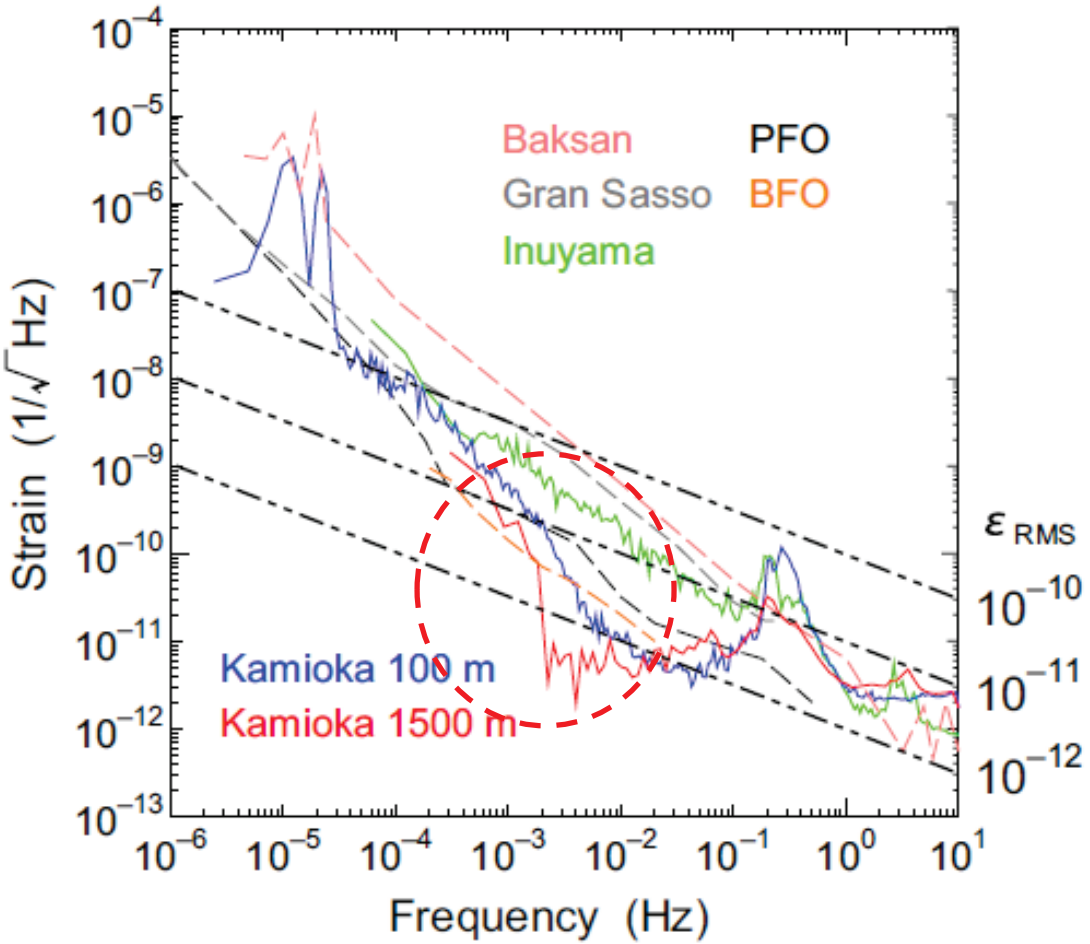


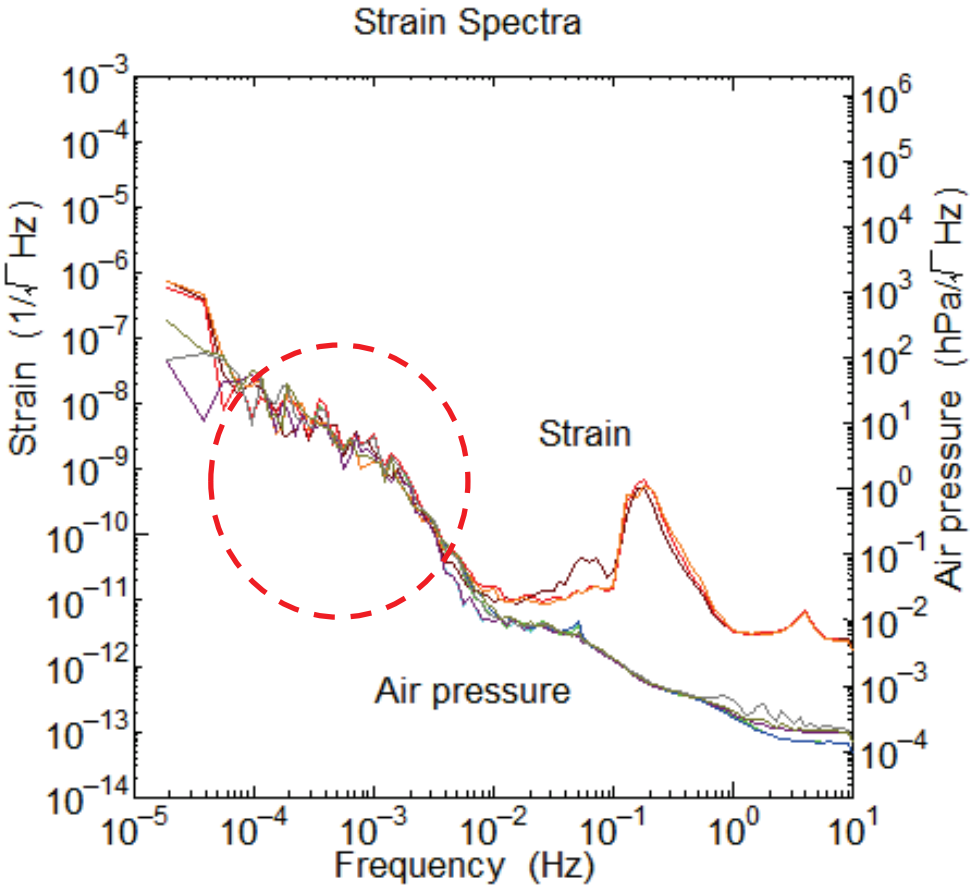
Barometric response

Strain in 10^{-4} – 10^{-3} -Hz region is highly dependent on the air pressure.

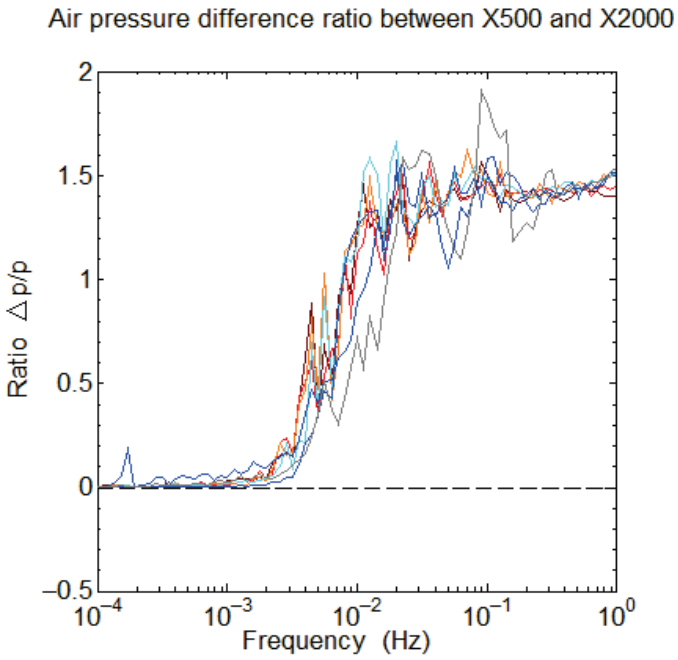
Barometric admittance

~0.55x10^{-9}/hPa

cf. 0.49x10^{-9}/hPa (Zürn, 2015)



Air-pressure relative difference between X500 and X2000. Both air pressure are identical (<10% difference) below ~3mHz and are uncorrelated above ~10mHz

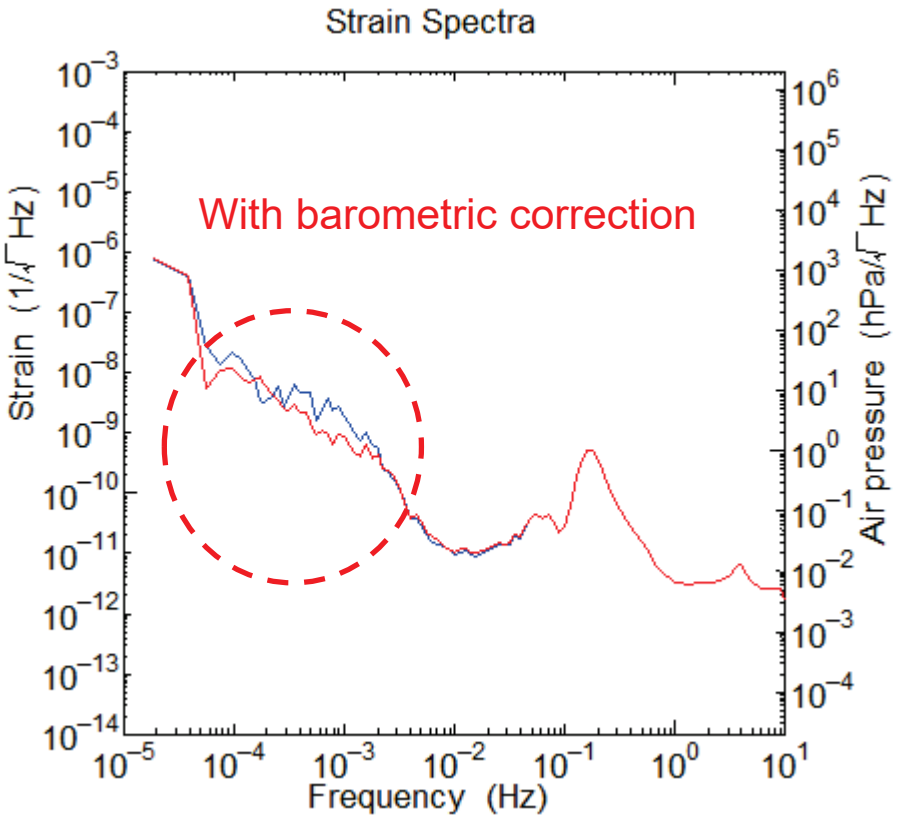


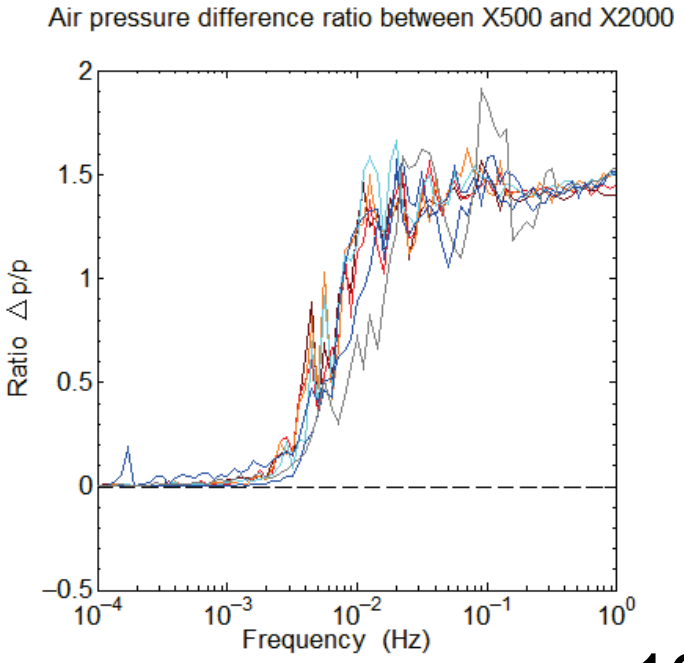
Barometric response

- Barometric correction reduces strain background to ~1/3 in the 10^{-4} – 10^{-3} -Hz region.

- The limited reduction suggests response of ground to regional air pressure (not the response of instruments to the local air pressure).

T. Akutsu et al., PTEP, 2021





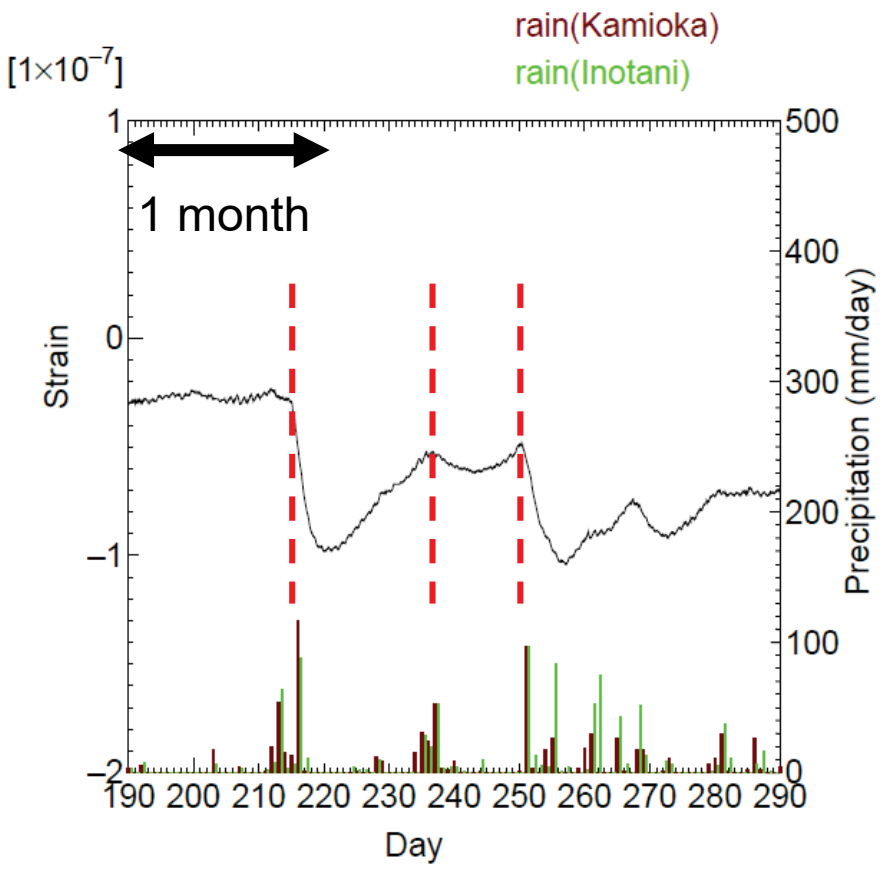
Long-term strains (June.- Sep. 2017)

-Averaged for every 10 min.

-Theoretical tides were
calculated and removed

Response to rain fall
…. due to change in
load of groudwater ?

~5x10^{-8} for 100mm rain-fall



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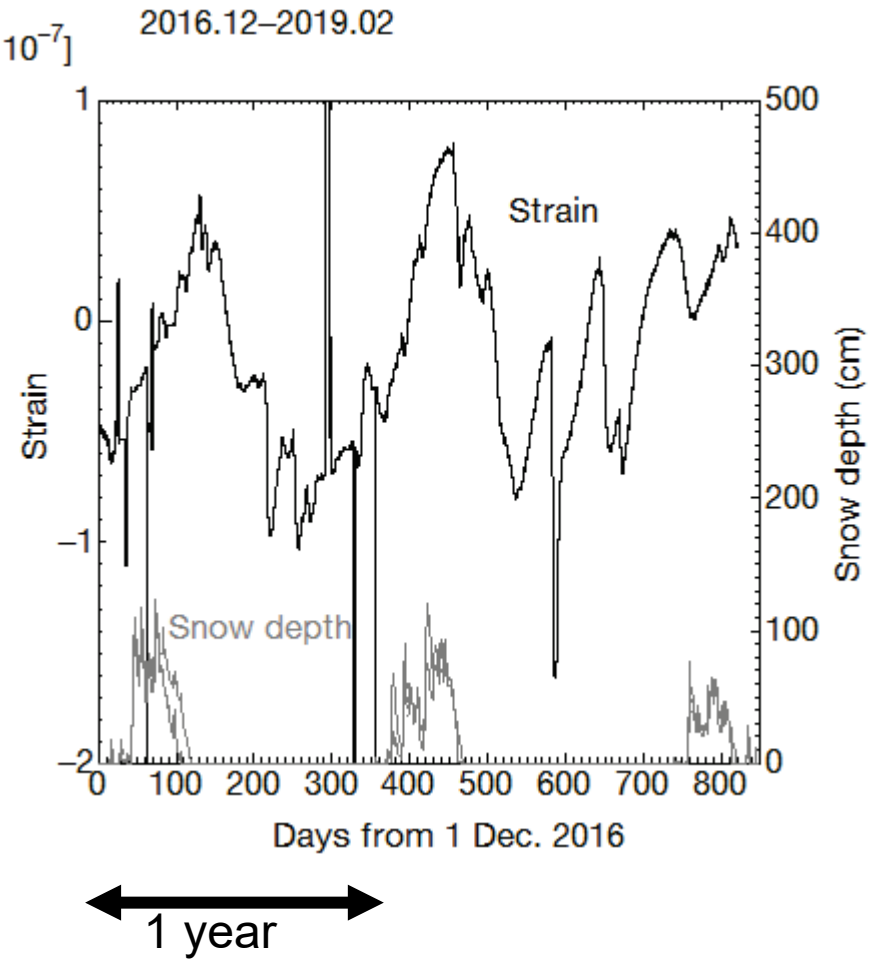
Long-term strains (Dec. 2016 – Feb. 2019)

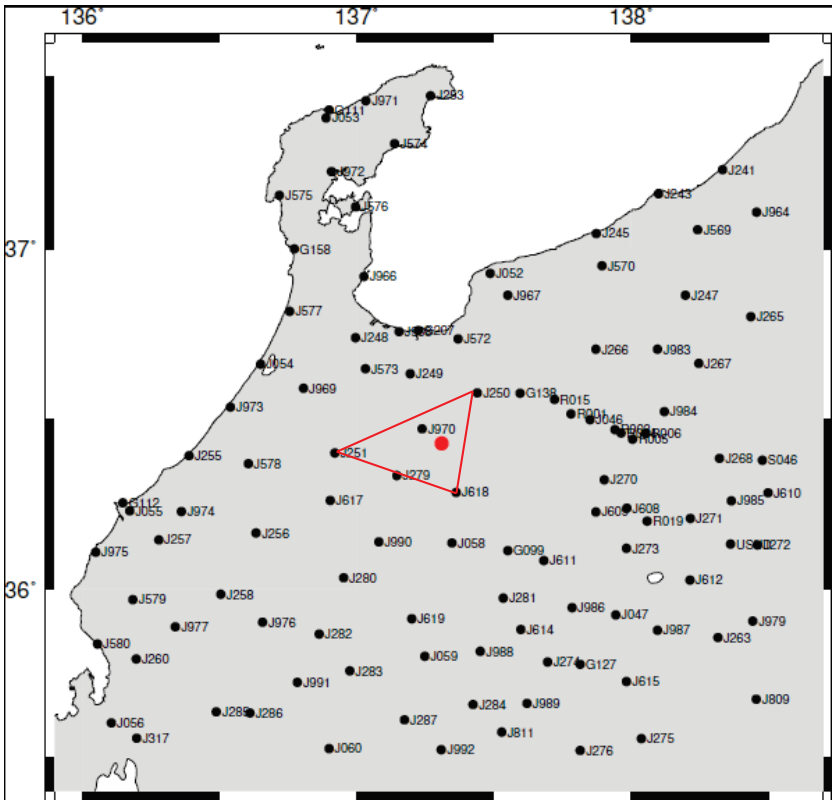
Response of snow load
~3x10^{-8} for 1-m snow depth

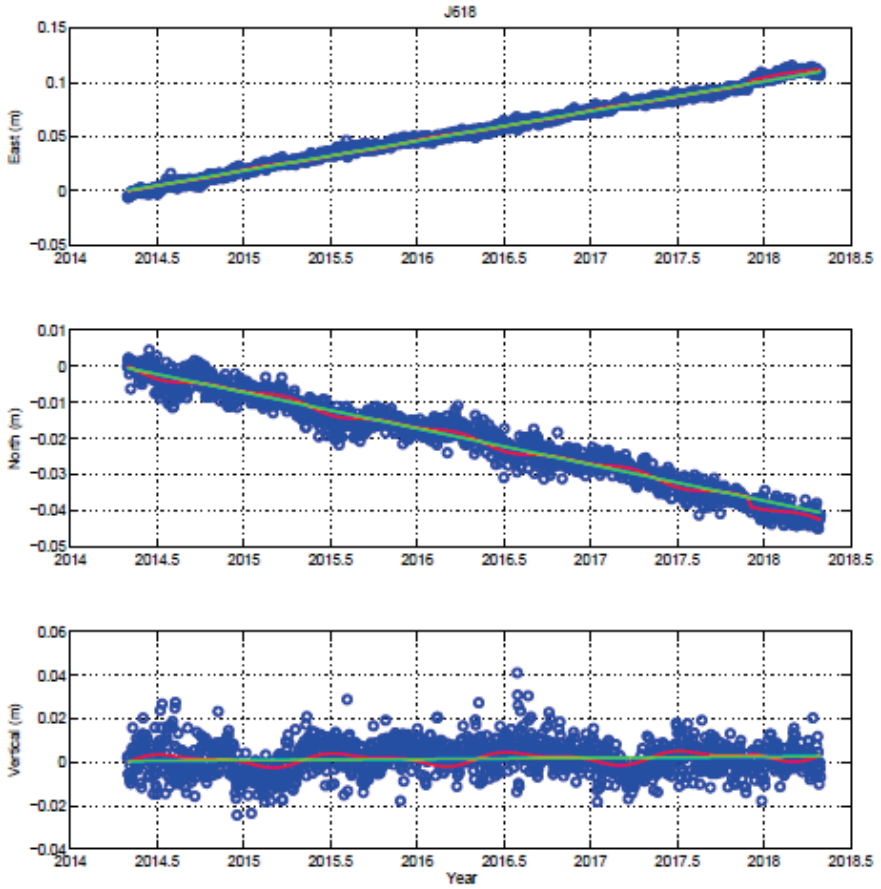
Data of snow depth (not at the mountain) were obtained from AMEDAS (Inotani and Kamioka)



Long-term strains (Dec. 2016 – Feb. 2019)

Regional ground strain around KAGRA site measured by GNSS



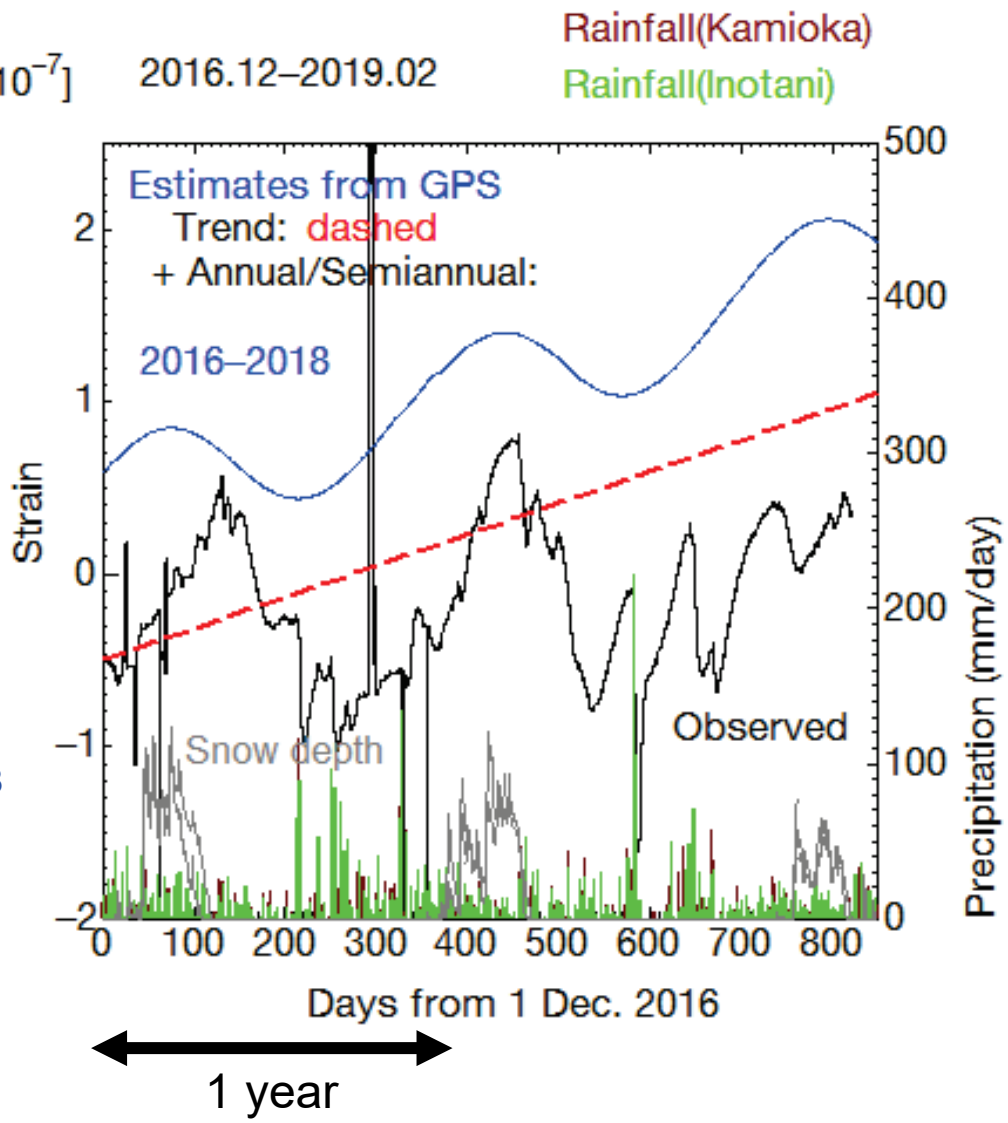


Long-term strains (Dec. 2016 – Feb. 2019)

Rainfall response
~5x10^{-8} /100-mm rainfall

Snow load response
~3x10^{-8}/1-m snow depth

roughly consistent
with GNSS estimates:
Trend: ~7x10^{-8} /year
Seasonal change: ~6x10^{-8}



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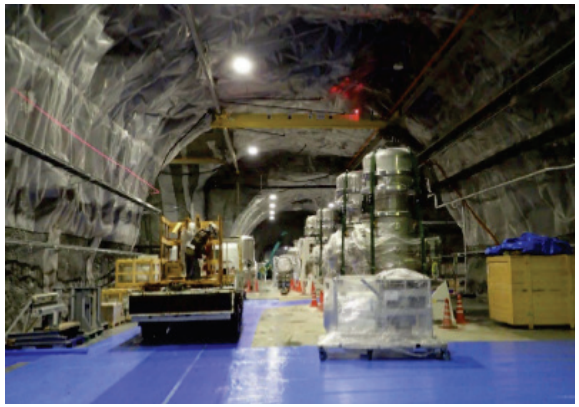
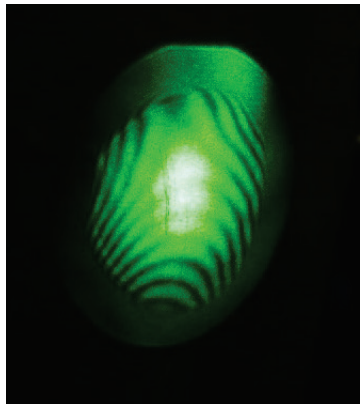
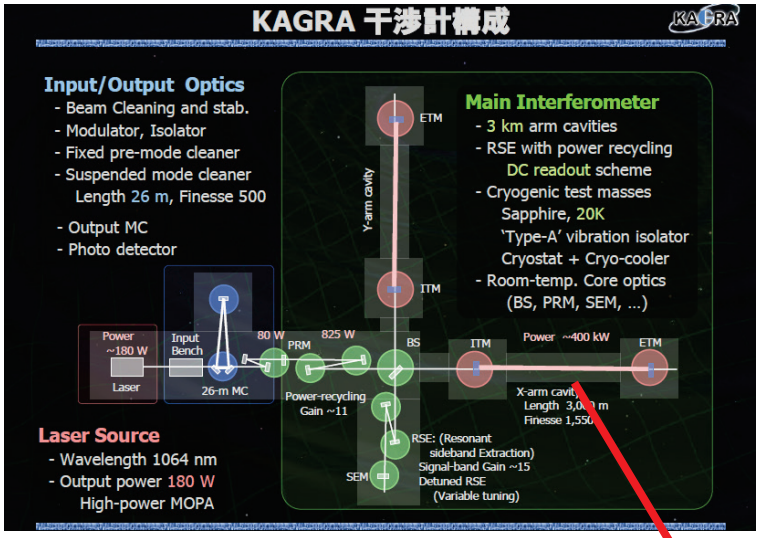
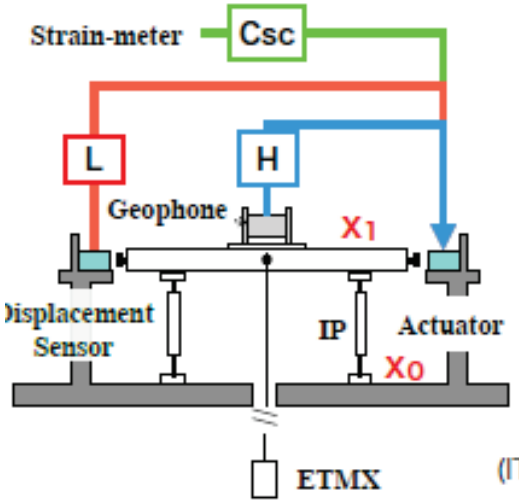
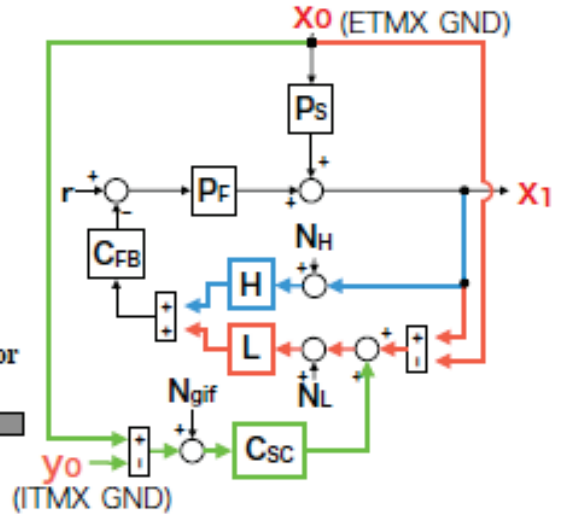
4. Demonstration of the arm-length control of KAGRA

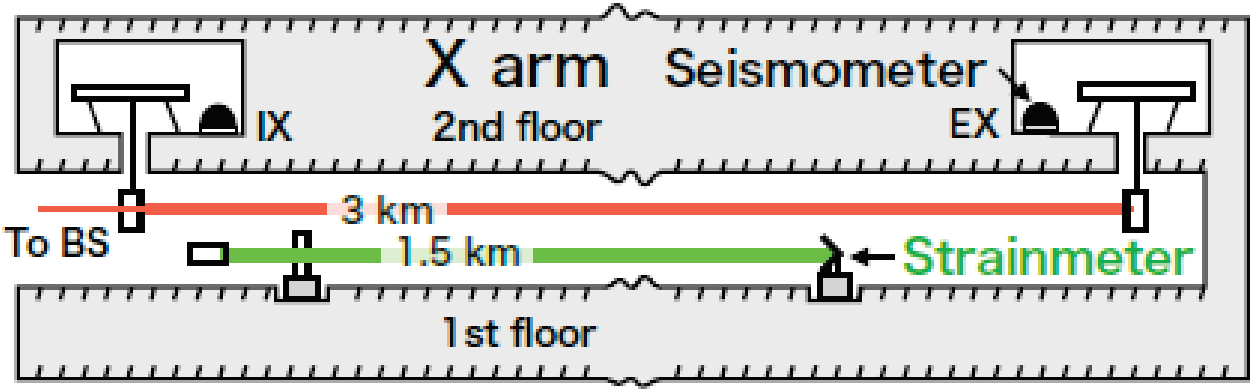





Feedforward control of arm length of KAGRA using the strainmeter signal.









Feedforward control of arm length of KAGRA using the strainmeter signal.

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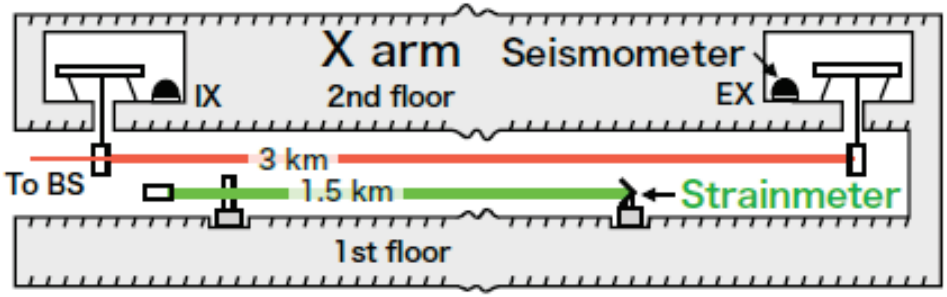
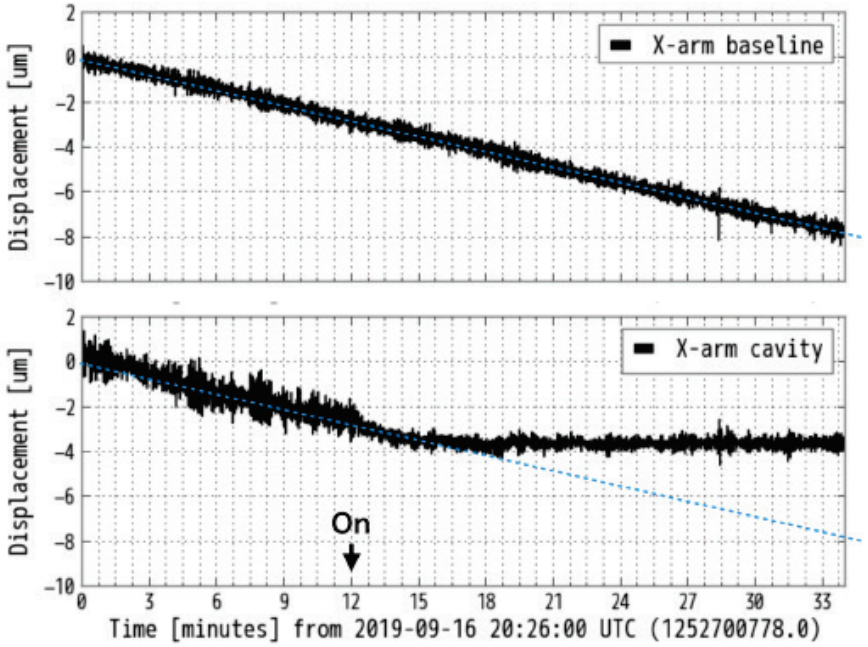
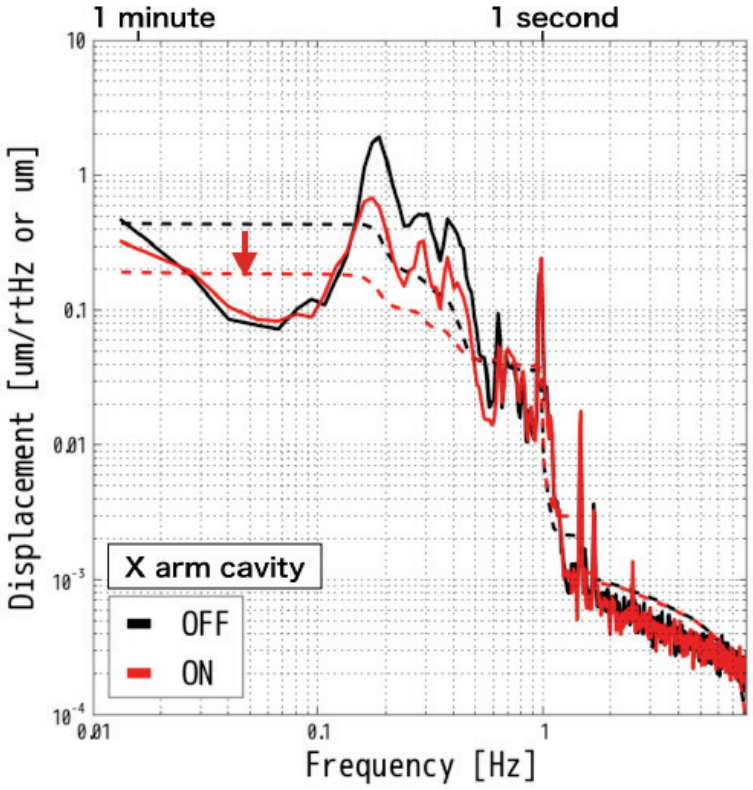




Baseline motions observed by the GIF (top) and the change in length of the KAGRA X-arm cavity (bottom).



RMS of cavity length mainly due to microseisms reduced to ~50 %

Conclusions

1. A 1500-m laser strainmeter in KAGRA has been in operation since 2016 and observed various ground strains at low frequencies.

2. Regional air pressures seem to affect ground strains in the millihertz band.

3. Temporal responses of ground strain to rainfall (contraction) and snow load (extension) was observed in Kamioka. Tectonic trends and seasonal changes are roughly consistent with estimates from GNSS.

4. Feedforward control of arm length of KAGRA using the strainmeter signal shows reduction of arm length change due to tides and microseisms.

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