Sixteenth Marcel Grossmann Meeting, session PT3
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On Zoom

Test of gravitational redshift with optical lattice clocks and their applications to relativistic geodesy

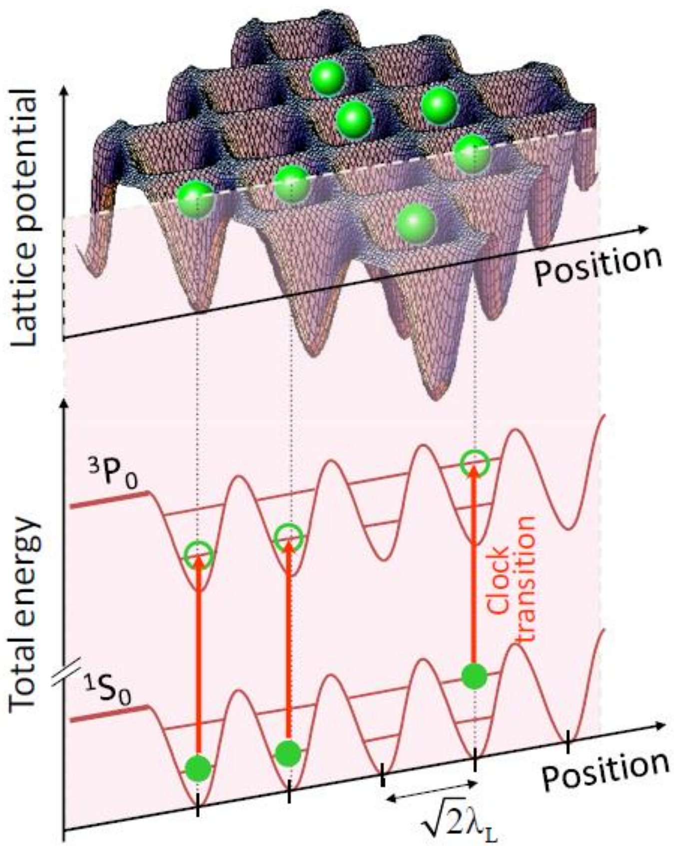
[1]Quantum Metrology Laboratory, CPR, RIKEN
[2]Space-Time Engineering Research Team, RAP, RIKEN
[3]Department of Applied Physics, Graduate School of Engineering, The University of Tokyo

[1,2]Masao Takamoto, [3]Ichiro Ushijima,
[1,2,3]Hidetoshi Katori

This work is supported by the JST project
"Space-time information platform with a cloud of optical lattice clocks"

Introduction to an optical lattice clock

To achieve "accurate" and "stable" clocks at $\delta\nu/\nu_0 = 10^{-18}$



Optical lattice potential confines millions of neutral atoms in separate micro-traps

- Strong confinement suppresses atomic thermal motion and allows "***Doppler-free***" spectroscopy
- Tuning the lattice laser to the "***magic frequency*** $\boldsymbol{\nu_m}$", "***light-shift-free***" confinement can be realized at the lowest order

$$h\nu = h\nu_0 - \frac{1}{2}\Delta\alpha(\nu_m)E^2 + O(E^4), \quad \Delta\alpha(\nu_m) = 0$$

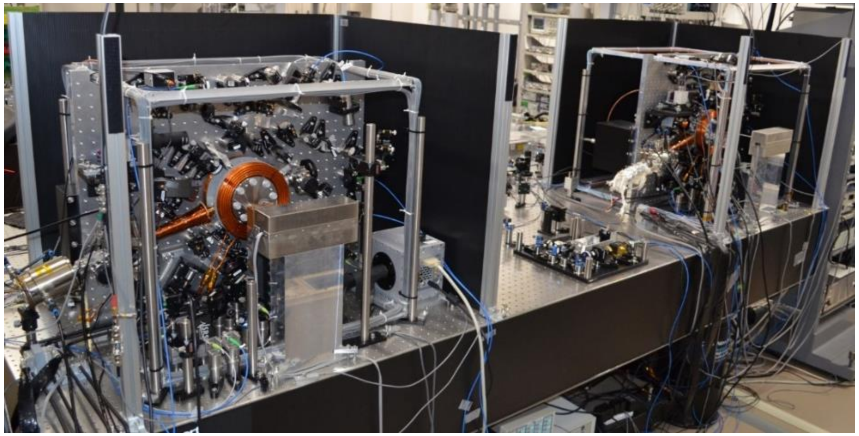
- Probing a large number of atoms improves the "***stability***" of the clock ($\sigma \propto 1/\sqrt{N}$)

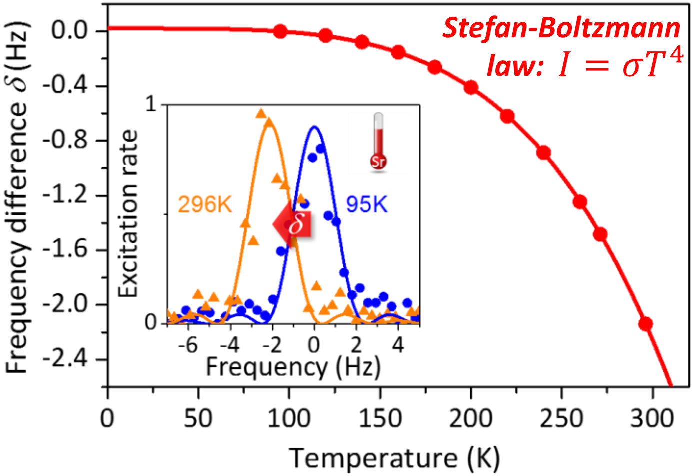
Proposal: *Katori, FMS (2001)*
Theory: *Katori, Takamoto, Pal'chikov & Ovsiannikov, PRL (2003)*
Demo.: *Takamoto, Katori, PRL (2003)*

Accuracy of 10^{-18}, two orders of magnitude higher than the accuracy of cesium clocks that define the "second", can be achieved in a short averaging time

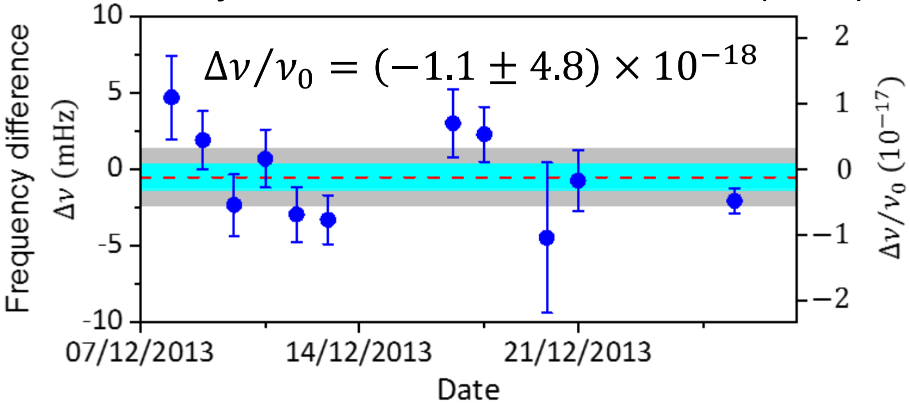
Realization of optical lattice clocks with 10^{-18} uncertainty

- Development of cryogenic optical lattice clocks to reduce blackbody radiation shift by probing atoms inside cryogenic shield
- Two optical lattice clocks agree with 10^{-18} uncertainty





I. Ushijima et al., Nat. Photon. 9, 185 (2015)



Optical clocks with 10^{-18} uncertainties or below

OLCs: Sr and Yb (Sr) T. Nicholson *et al*., Nat. Commun. 6, 6896 (2015)

(Yb) W. F. McGrew *et al*., Nature 564, 87 (2018)

Ion clocks: Al^+ and Yb^+ (Al^+) S. M. Brewer *et al*., *Phys. Rev. Lett.* 123, 033201 (2019)

(Yb^+) N. Huntemann *et al*., *Phys. Rev. Lett*. 116, 063001 (2016)

Application of optical lattice clocks to relativistic geodesy

Einstein's theory of general relativity

"A clock in a higher altitude ticks faster than one in a lower altitude due to gravity"

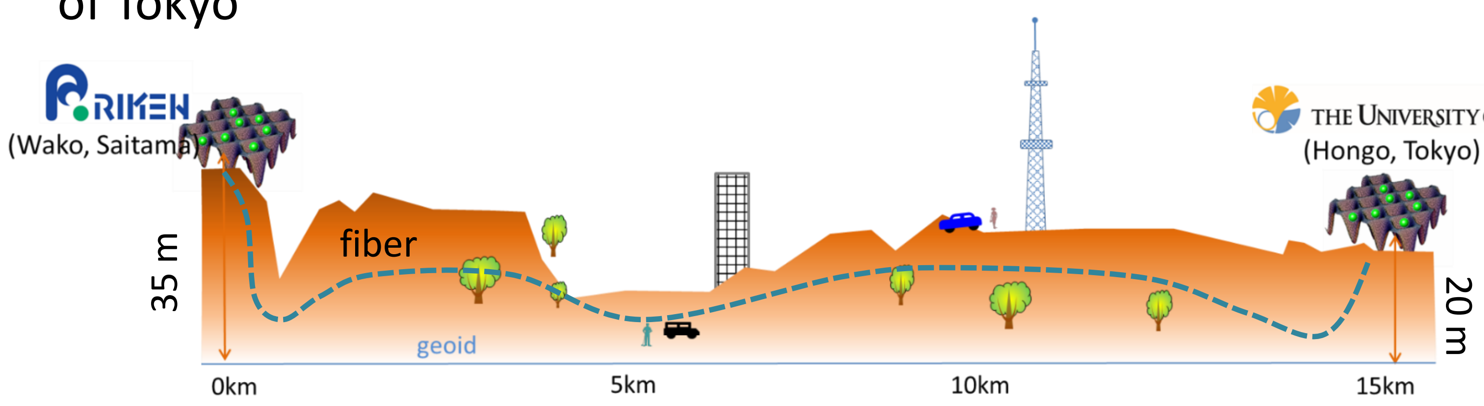
$$\frac{\delta\nu}{\nu} = \frac{g\Delta h}{c^2}$$

- Height difference $\Delta h = 1$ cm causes time dilation of $\delta\nu/\nu \approx 10^{-18}$
- The accurate clock becomes a precise probe of gravitational potential
- The clock becomes a system of elevation that defines the equipotential surface: "Quantum benchmark"

Ref. "Chronometric levelling"
M. Vermeer, Rep. Finnish Geodetic Inst. 83, 1 (1983)

Demonstration of relativistic geodesy

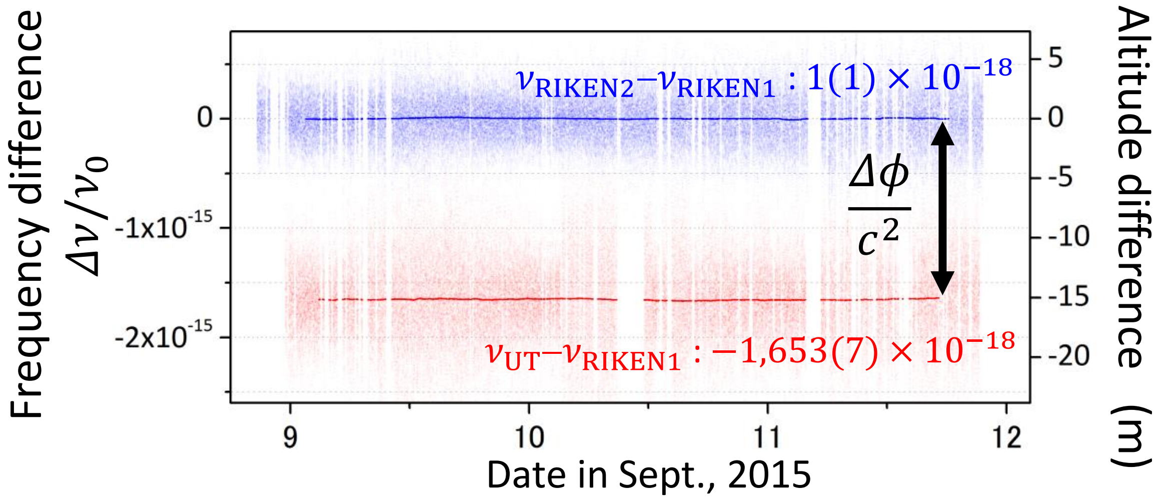
- Frequency comparison of remote optical lattice clocks in RIKEN and The Univ. of Tokyo



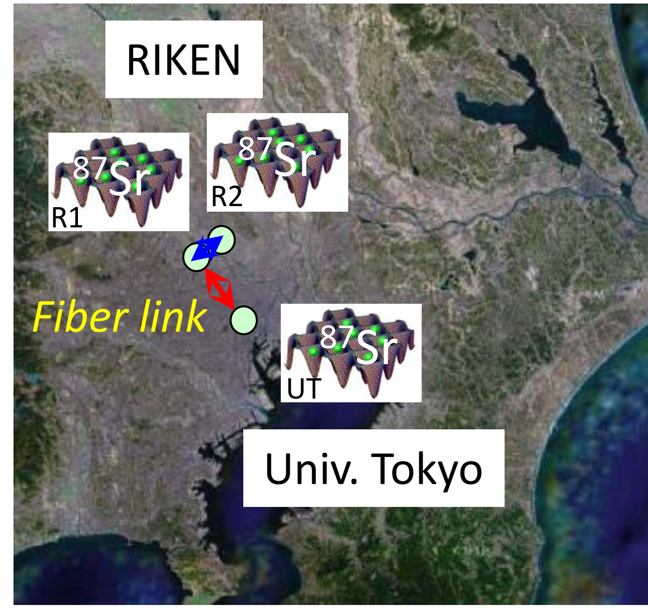
Altitude difference $\Delta h \sim 15$ m

T. Takano et al., Nat. Photon. 10, 1038 (2016)

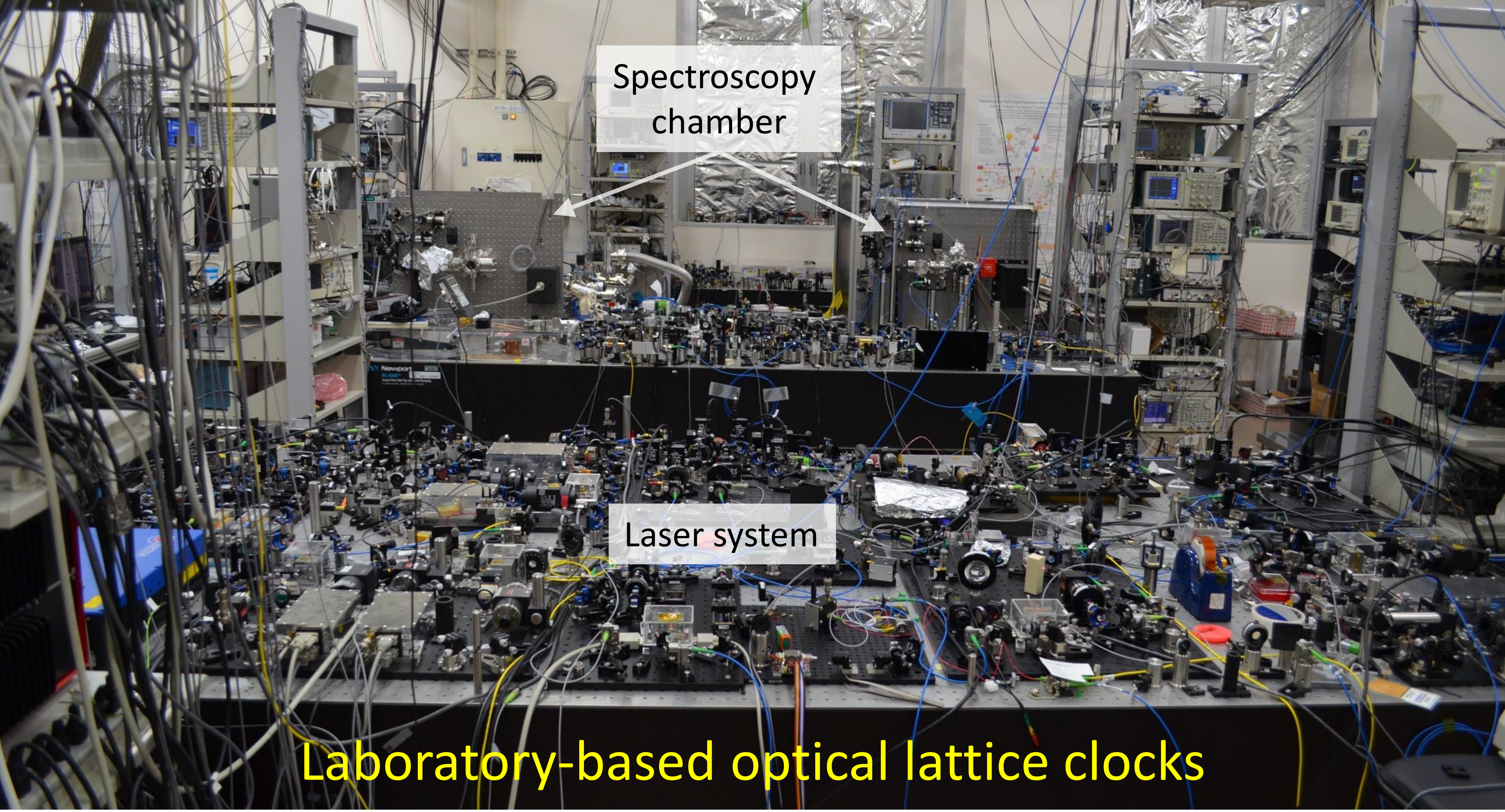
Remote frequency comparison between RIKEN and UT（’16）



T. Takano et al., Nat. Photon. 10, 1038 (2016)



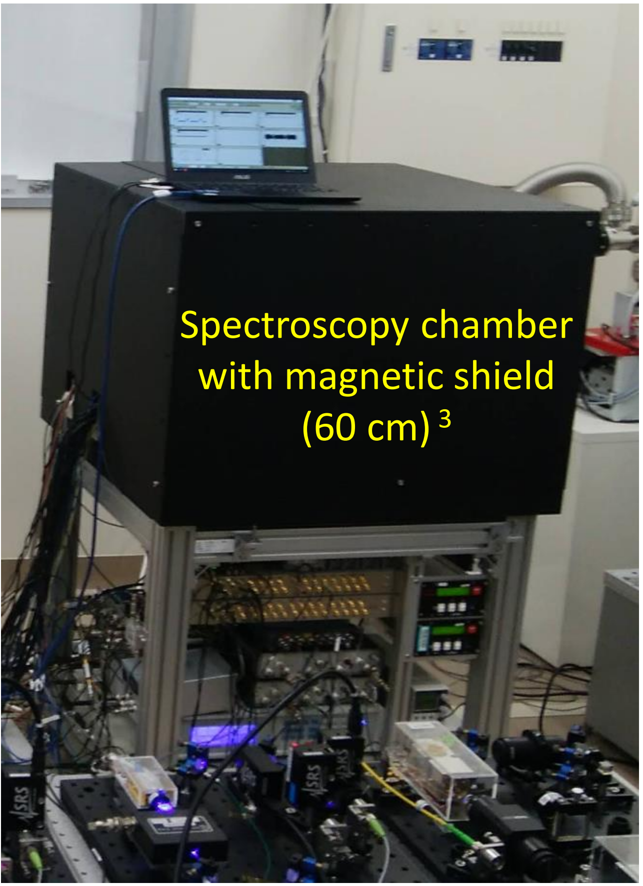
- Observe the altitude (gravitational potential) difference between RIKEN (Wako) and the University of Tokyo (Hongo, Bunkyo-ku) in real time by clock comparison
- Good agreement with conventional leveling survey performed by Geospatial Information Authority of Japan
- Laboratory-based fixed-point measurement was realized
- In order to further expand its application as a measurement tool, the clock system needs to be transportable

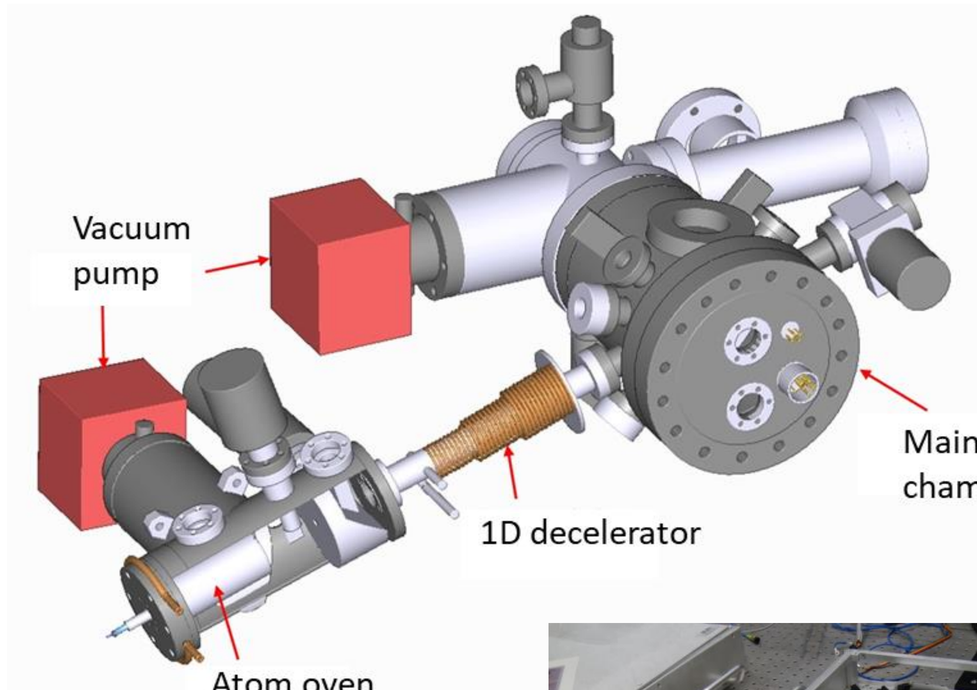


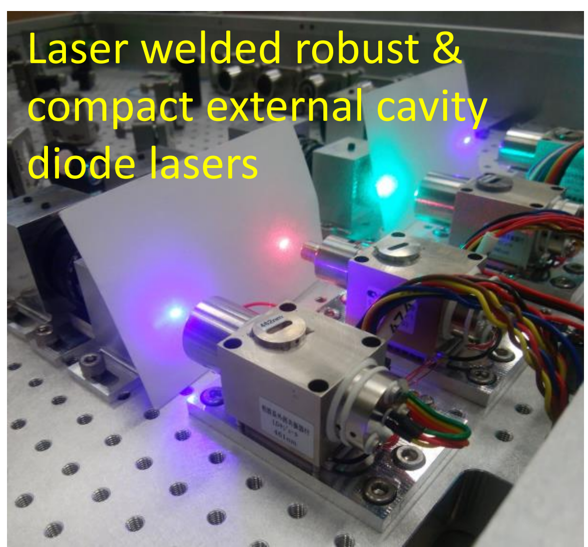
- 18 frequency-stabilized lasers are required to operate two clocks
- The system works only inside the laboratory
- As a practical tool for measurement outside laboratory, development of more compact and transportable setups is required

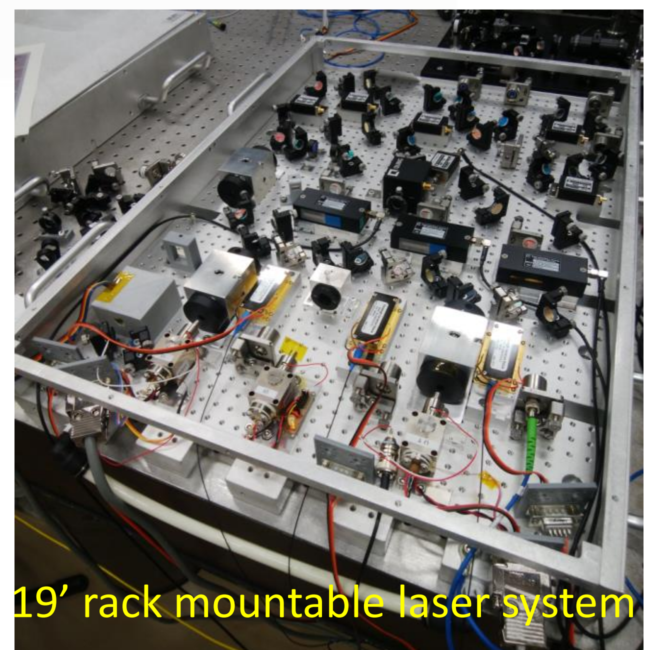
ref. Sr OLC in a trailer: S. B. Koller et al., PRL 118, 073601 (2017)

Transportable Optical Lattice Clocks

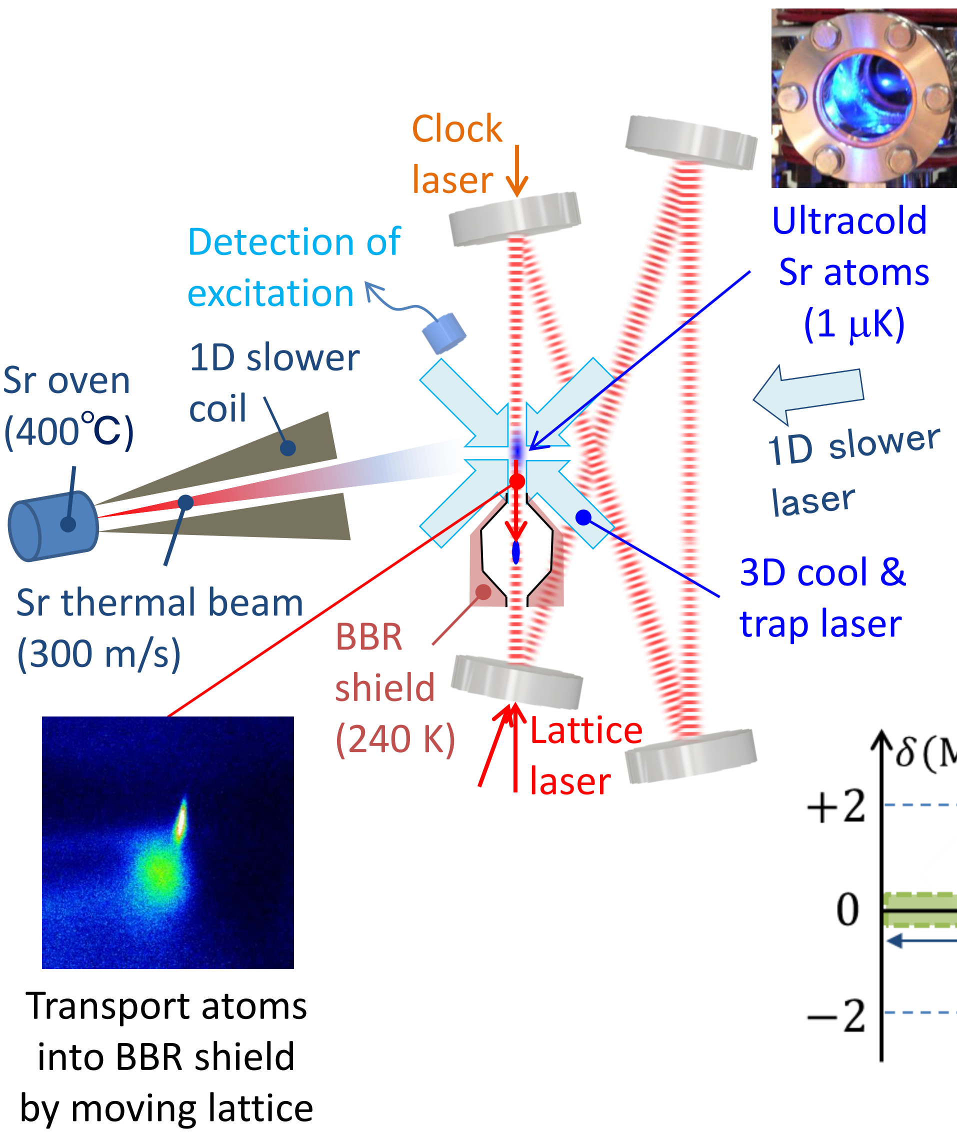








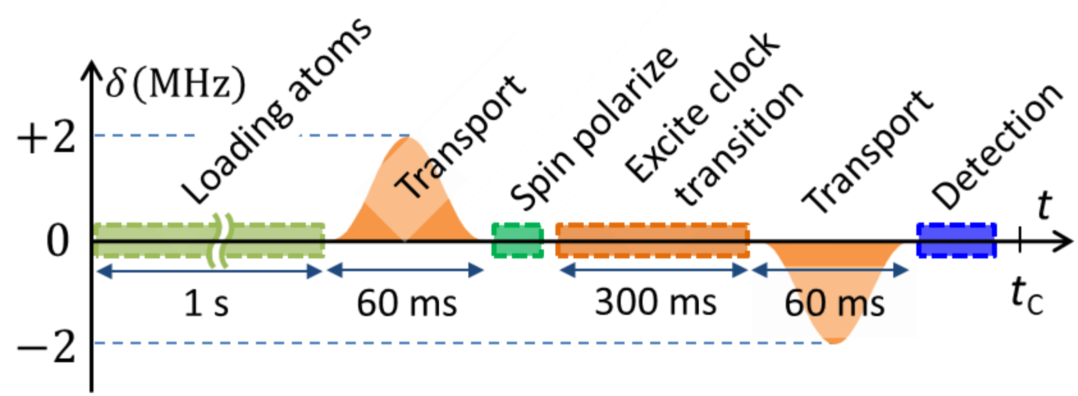
1D optical lattice inside a ring cavity



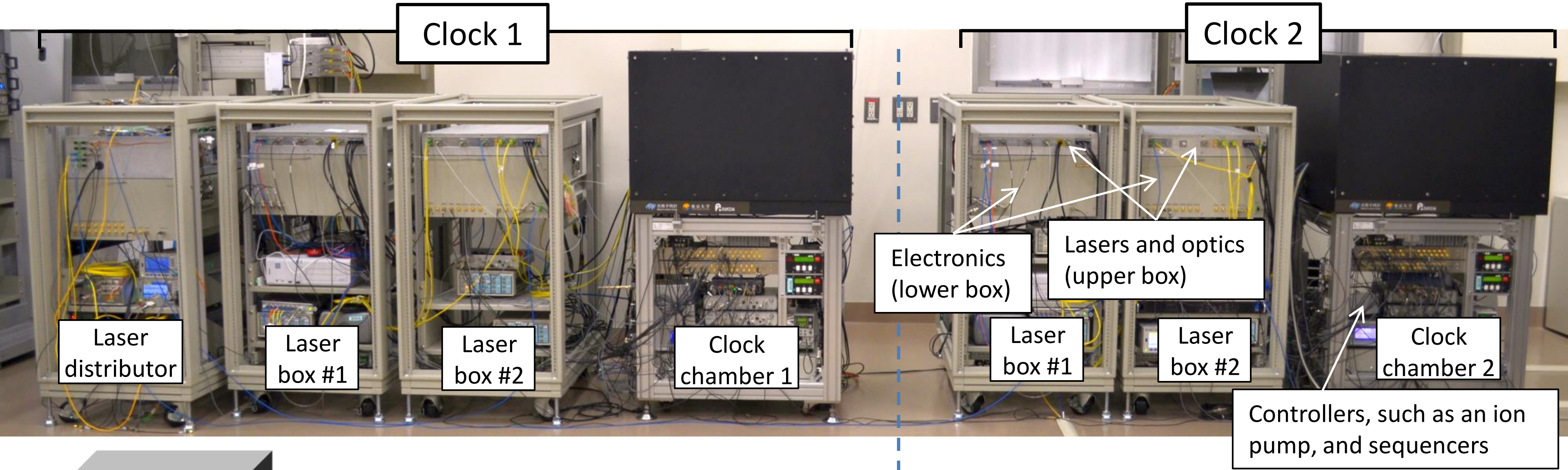
Clock sequence

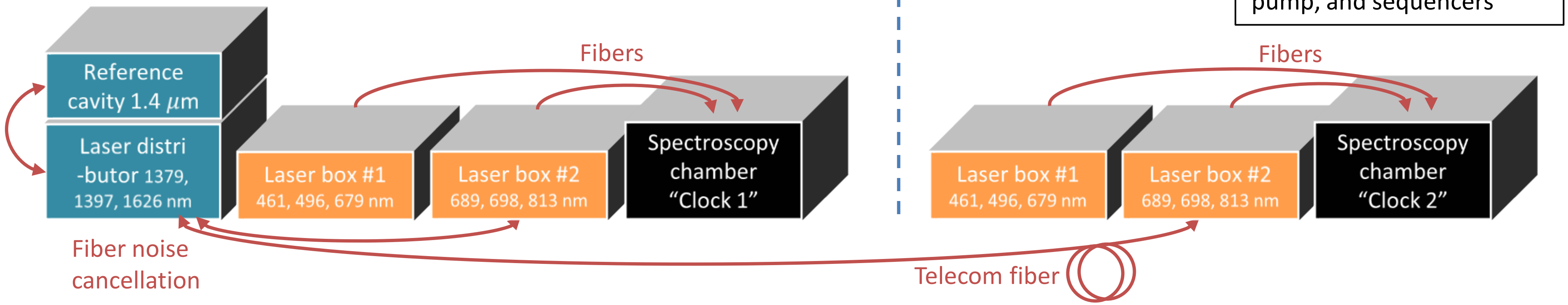
1. *Load atoms into lattice*
2. *Transport atoms into BBR shield*
3. *Excite clock transition*
4. *Transport atoms back to outside*
5. *Measure excitation rate*
6. *Feedback to laser frequency to keep resonant to Sr transition*

Repeat
t_C=1.6 s



A pair of transportable clocks connected by a fiber link

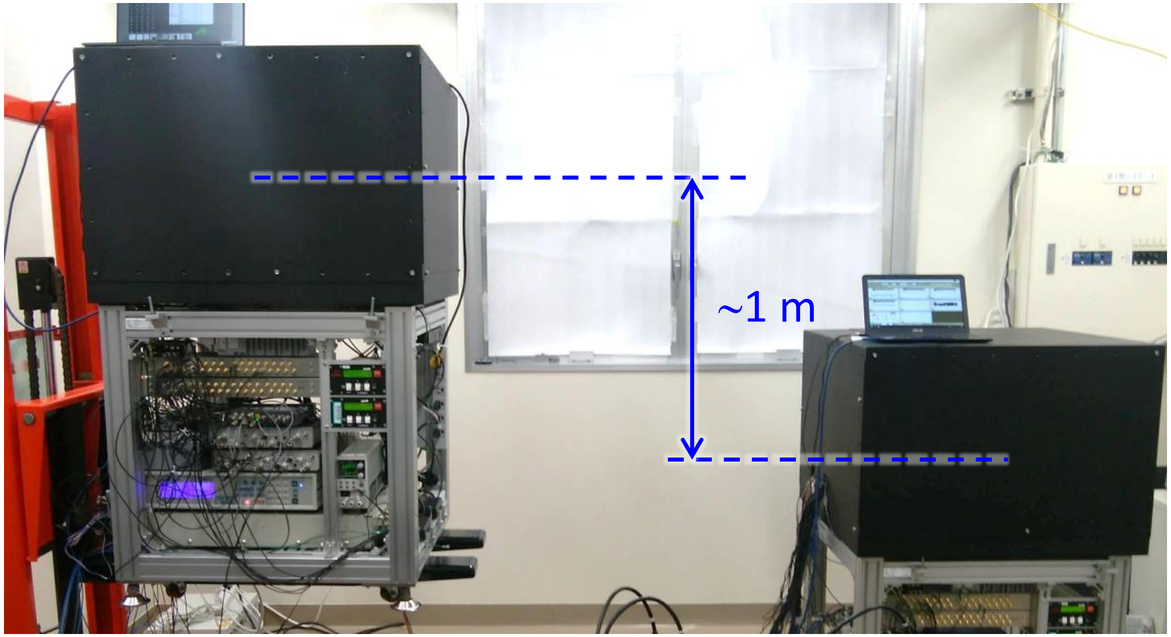


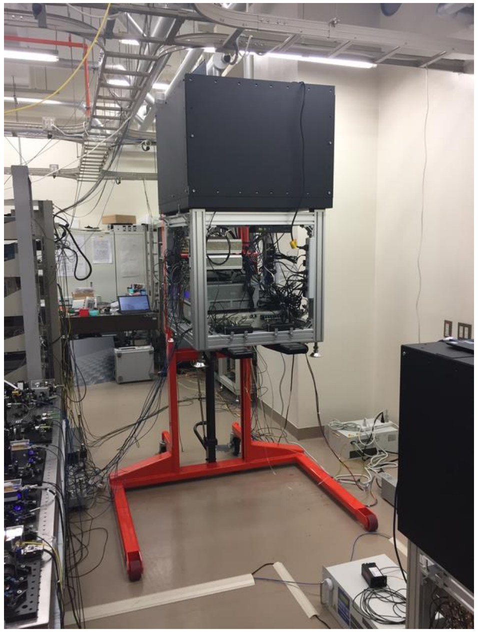


- Laser systems with control electronics mounted on 19 inch racks
- Laser box #1: cooling (461, 496 nm), pumping (679 nm) lasers
- Laser box #2: narrow-line cooling (689 nm), lattice (813 nm), clock (698 nm) lasers
- Both clocks are connected by a noise canceled telecom fiber to send cavity-stabilized reference lasers at subharmonics from a laser distributor

Preliminary experiment in laboratory:
Measure height difference of 1 m by comparing two clocks

- Lift up one of two clocks and compare their clock frequencies
- Measure gravitational time dilation for 1 m height difference with an averaging time of a few minutes





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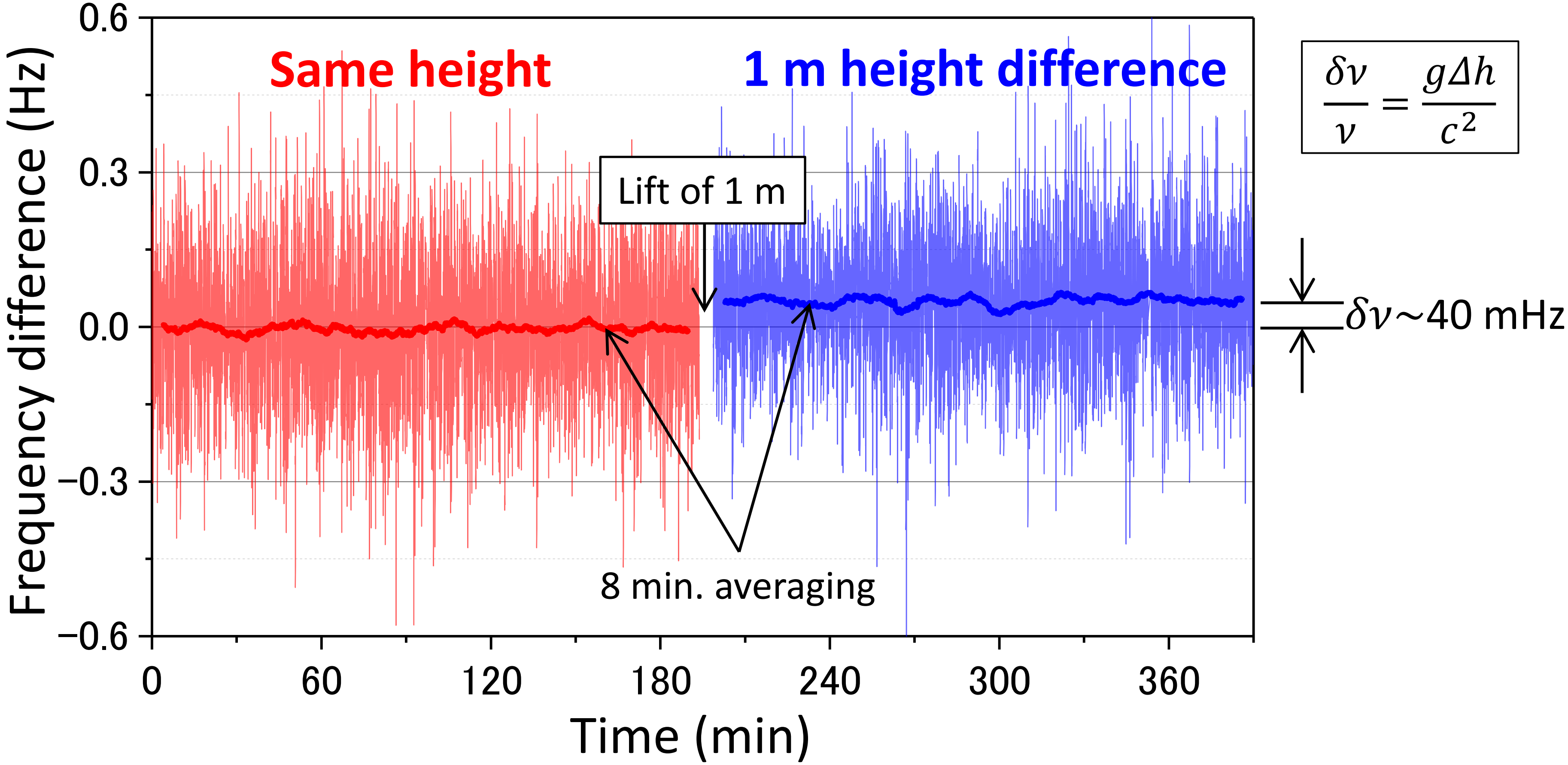


Time dilation for 1 m height difference due to general relativity is resolved by comparing optical lattice clocks with a few minutes of averaging time

Test of general relativity

- Optical lattice clocks set at 0 m and 450 m in TOKYO SKYTREE
- Connect two clocks with an optical fiber and measure gravitational redshift for height difference of 450 m
  - Gravitational redshift for $450\ \mathrm{m}$: $\sim 21\ \mathrm{Hz}\ (5 \times 10^{-14})$
  - Accuracy of redshift: $1 \times 10^{-18}/(5 \times 10^{-14}) \sim 2 \times 10^{-5}$
- Measure height difference by laser ranging and Global Navigation Satellite System (GNSS) and gravity by gravimeter

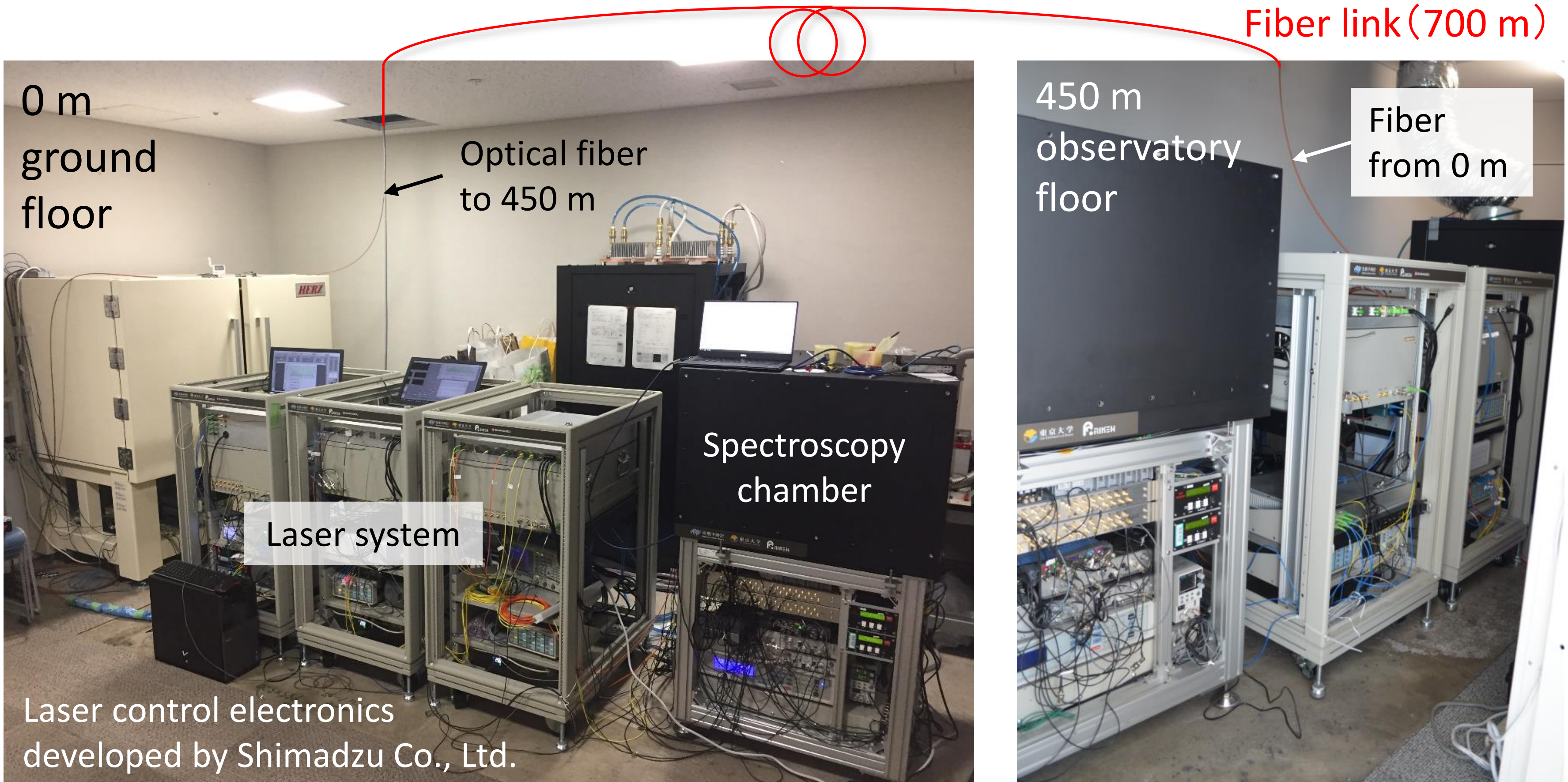
$$\delta\nu_{\mathrm{redshift}}/\nu_0 = (1 + \alpha)\, g\Delta h/c^2$$

- Previous experiments to test GR
  - Pound-Rebka-Snider experiment (Harvard tower: $\Delta h = 23\ \mathrm{m}$)
    $|\alpha| < O(10^{-2})$ (PRL 4, 337 (1960))
  - Gravity Probe A mission, NASA (H-maser in spacecraft: $\Delta h \approx 10{,}000\ \mathrm{km}$)
    $|\alpha| \approx 1.4 \times 10^{-4}$ (PRL 45, 2081 (1980))
  - Galileo satellites, ESA (Atomic clocks on elliptic orbits: $\Delta h \approx 8{,}500\ \mathrm{km}$)
    $\alpha = (0.19 \pm 2.48) \times 10^{-5}$ (PRL 121, 231101 (2018))
    $\alpha = (4.5 \pm 3.1) \times 10^{-5}$ (PRL 121, 231102 (2018))
- Test of GR with ground-based ($\Delta h \approx 0.5\ \mathrm{km} \ll 10^4\ \mathrm{km}$) experiment using accurate clocks

Installation of two clocks in TOKYO SKYTREE (Oct. 2, 2018)

Period of experiment:
Oct. 3, 2018 - Apr. 9, 2019

A pair of optical lattice clocks at 0 m and 450 m floor

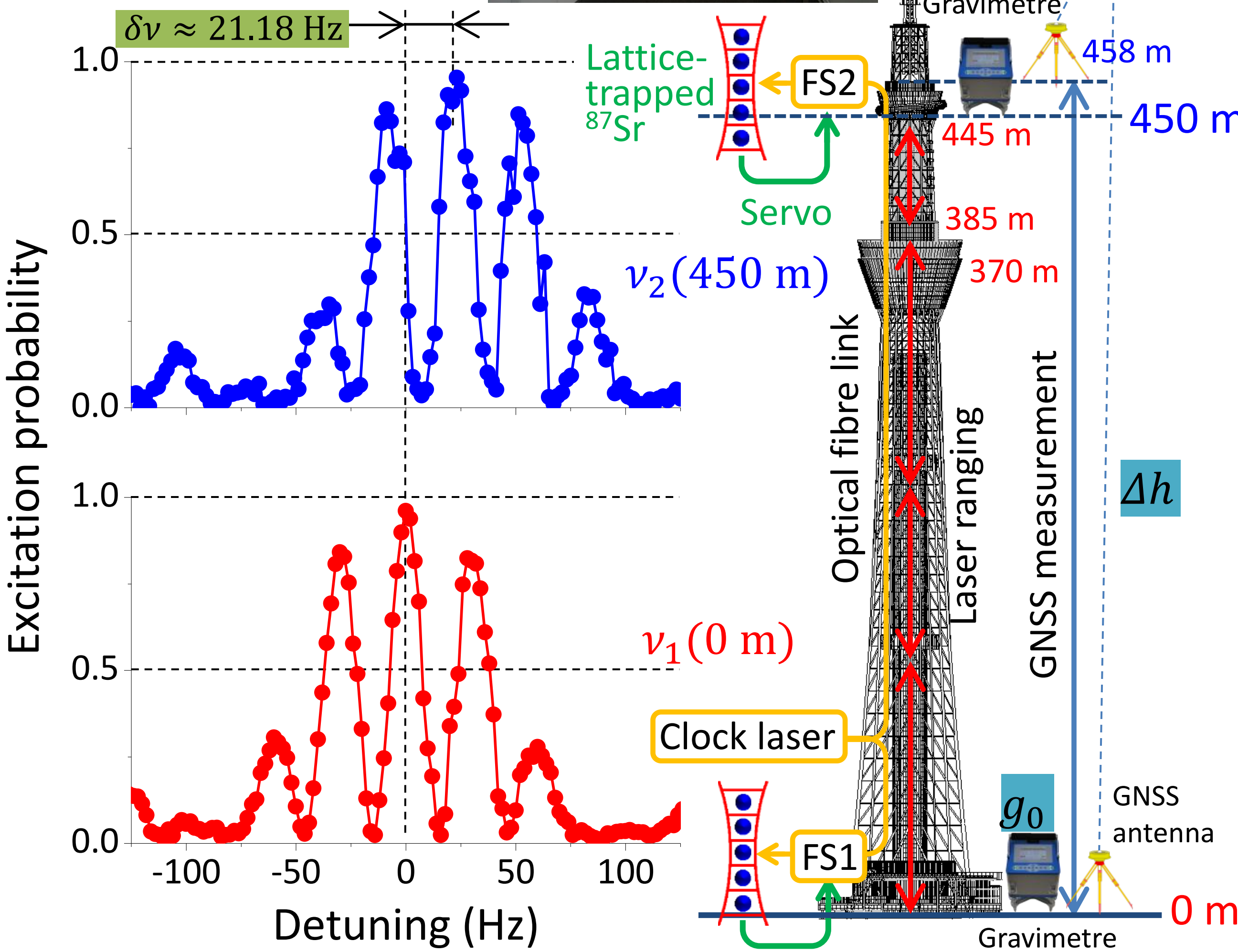


- Optical fiber link (700 m) with fiber noise cancelation system to compare clocks at 0 m and 450 m
- Automated operation with remote access
- Realization of stable operation even with diurnal environmental temperature change of 10 °C at TOKYO SKYTREE

Test of GR: gravitational redshift & height difference by surveying

$$\frac{\delta\nu}{\nu} = \frac{\bar{g}\Delta h}{c^2}$$

Clock comparison



Two ways of surveying

① GNSS (Geospatial authority of Japan)

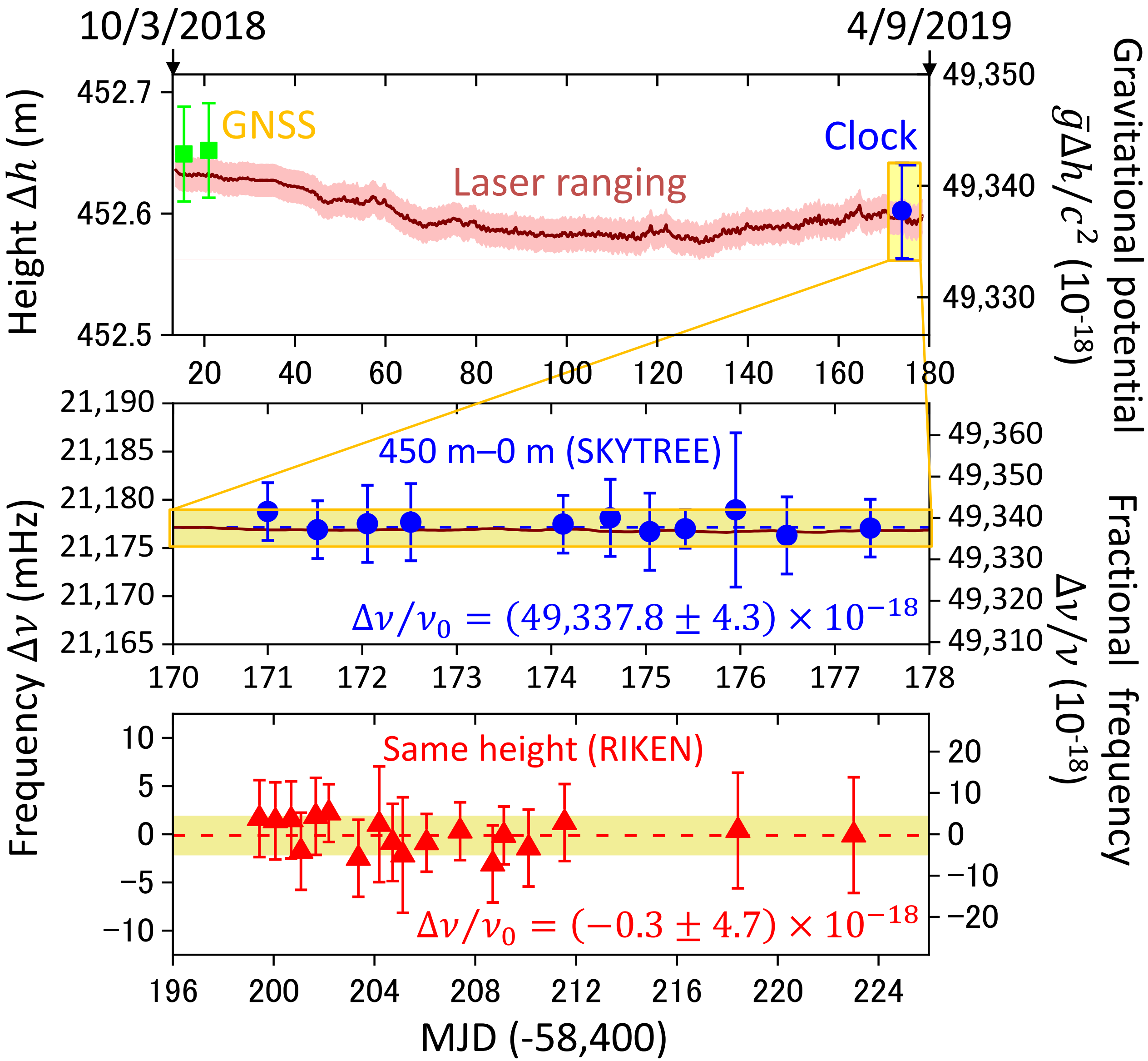
② Laser ranging

Laser ranging were performed by laser distance meter using an aperture near the central pillar of the tower

※ Short distance:

Spirit leveling by GSI

Test of GR：gravitational redshift & height difference by surveying



M. Takamoto, I. Ushijima, N. Ohmae, T. Yahagi, K. Kokado, H. Shinkai, and H. Katori, Nature Photon. 14, 411 (2020)

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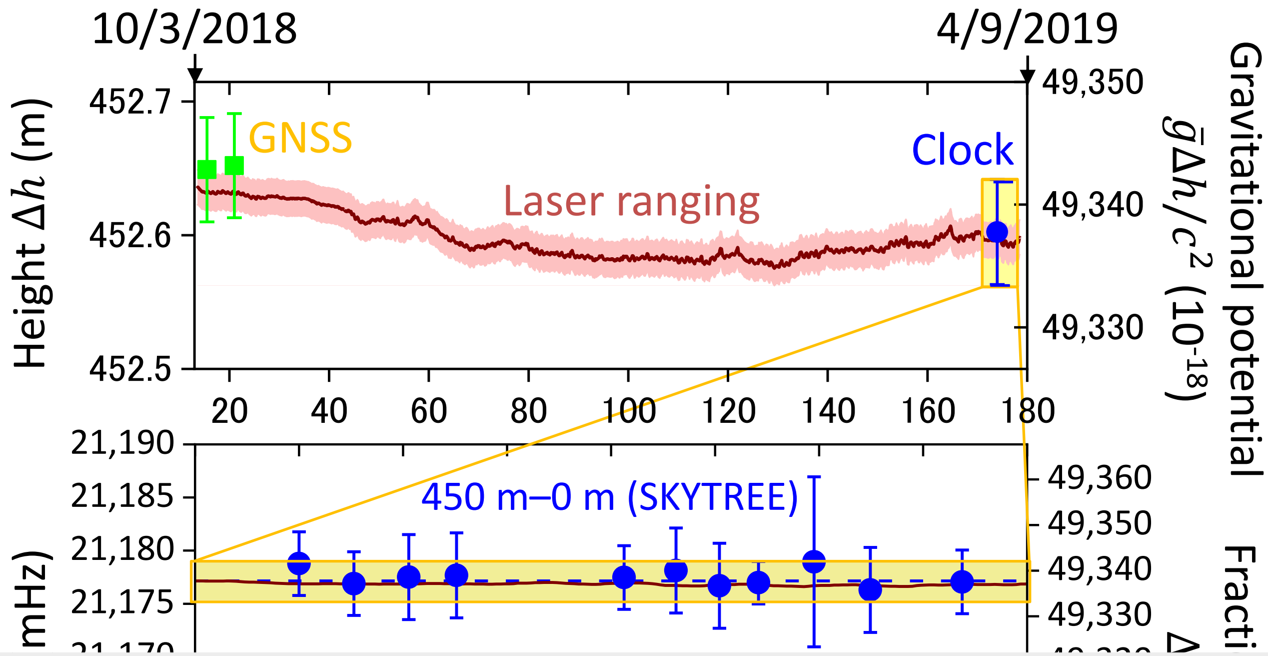
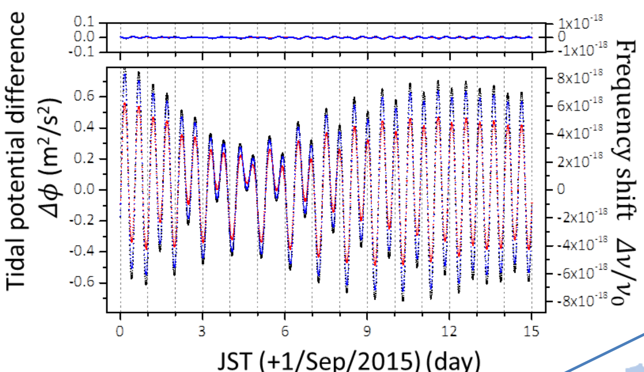


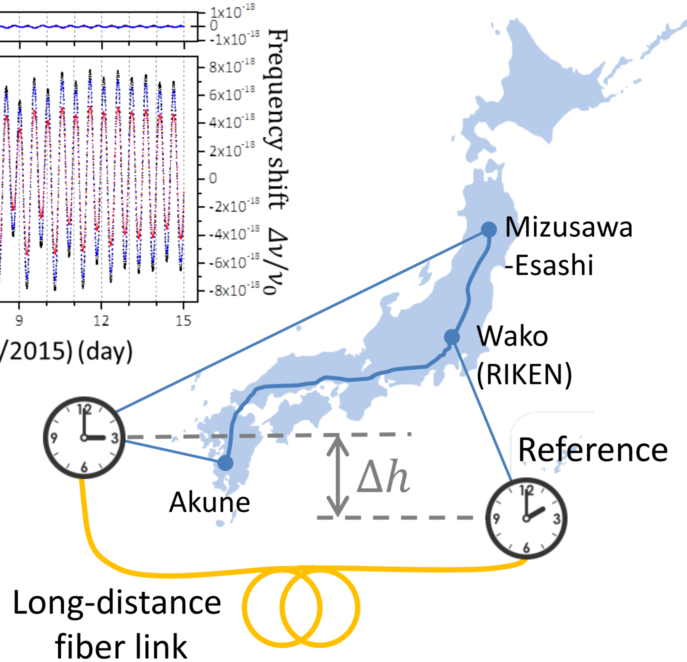
Measurement period	Height difference Δh (m) GNSS	Laser ranging	Clock f difference $\Delta\nu/\nu_1$ (10^{-18}) 450 m – 0 m	Same height
MJD 58,414 – 58,417	452.649(39)	452.632(13)	–	–
MJD 58,420 – 58,422	452.652(39)	452.631(13)	–	–
MJD 58,571 – 58,577	–	452.596(13)	49,337.8(4.3)	–
MJD 58,599 – 58,623	–	–	–	-0.3(4.7)
α parameter	$\alpha = \frac{\Delta\nu}{\nu_1}\frac{c^2}{\bar{g}\Delta h} - 1 = 1.4(9.1)\times 10^{-5}$			

M. Takamoto, I. Ushijima, N. Ohmae, T. Yahagi, K. Kokado, H. Shinkai, and H. Katori, Nature Photon. 14, 411 (2020)

Transportable optical lattice clock on vehicle

- Development of an on-vehicle optical lattice clock allows us to realize a gravitational potential meter that can operate in any location
- Using a 1000-km-scale long optical fiber link, we apply it to monitor crustal movement and tidal effects at the 10^{-18} level

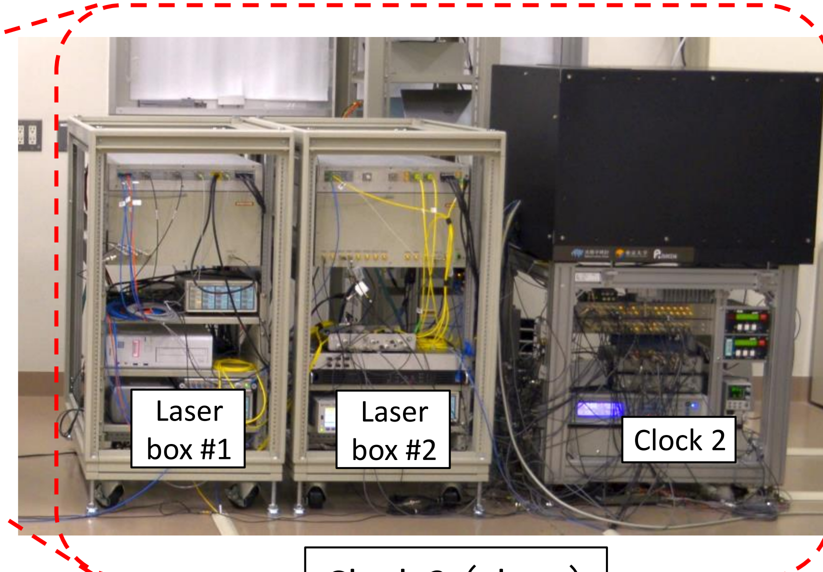




Tidal effect between Wako-Akune (970 km) ~10^{-17} , *Nat. Photon. 10, 1038 (2016)*

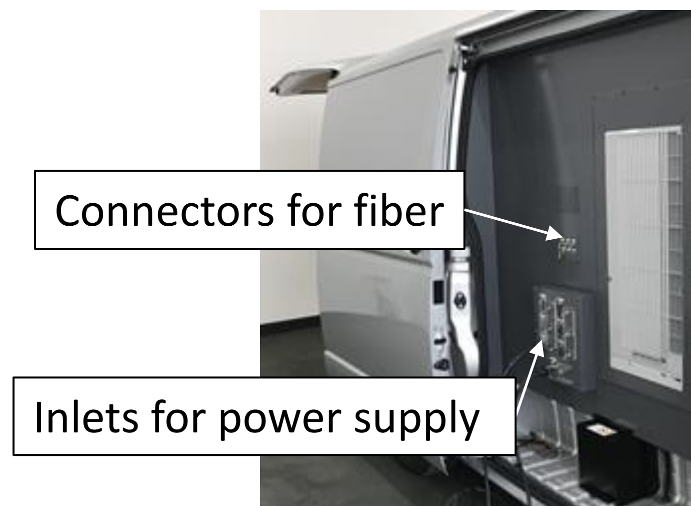
Transportable optical lattice clocks on vehicle

(TOYOTA Hiace, modified by AISIN Co., Ltd.)

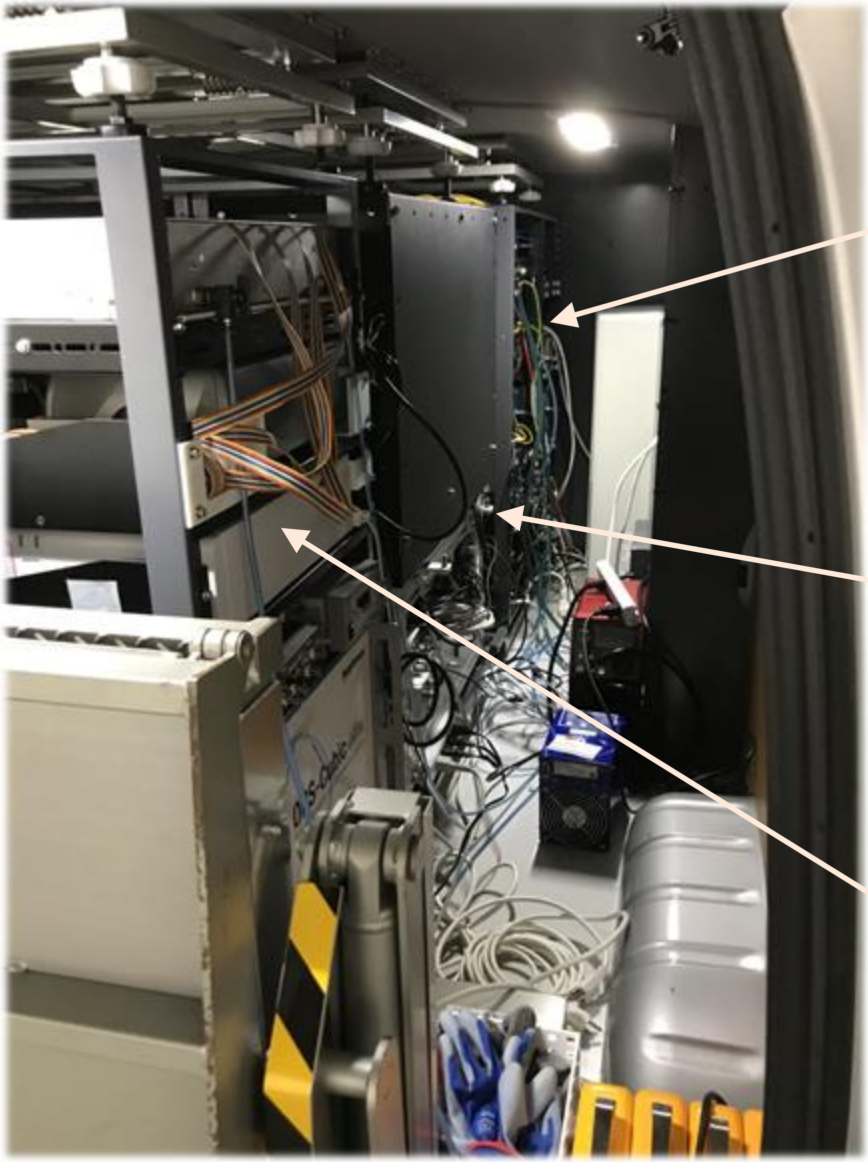


Clock 2（slave）

- Optical lattice clock (slave clock; 19-inch rack on the wagon by providinx3) loaded on a wagon
- Clock can be operated g power supply
- By connecting an optical fiber to transfer the clock frequency, the clock can be compared with reference clocks



Overall view of the on-vehicle clock setup



Rack #1

- Laser sources for spectroscopy （Clock 698 nm, Lattice 813 nm, Cooling 689 nm）
- Broadband reference cavity

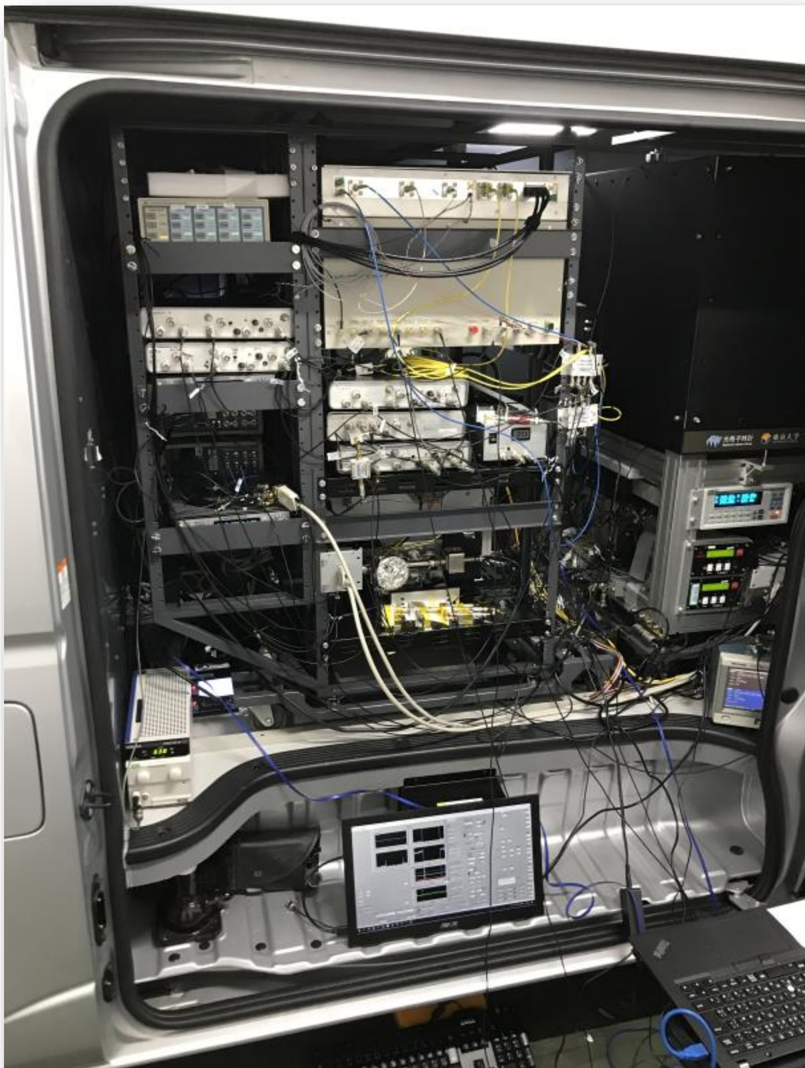
Rack #2

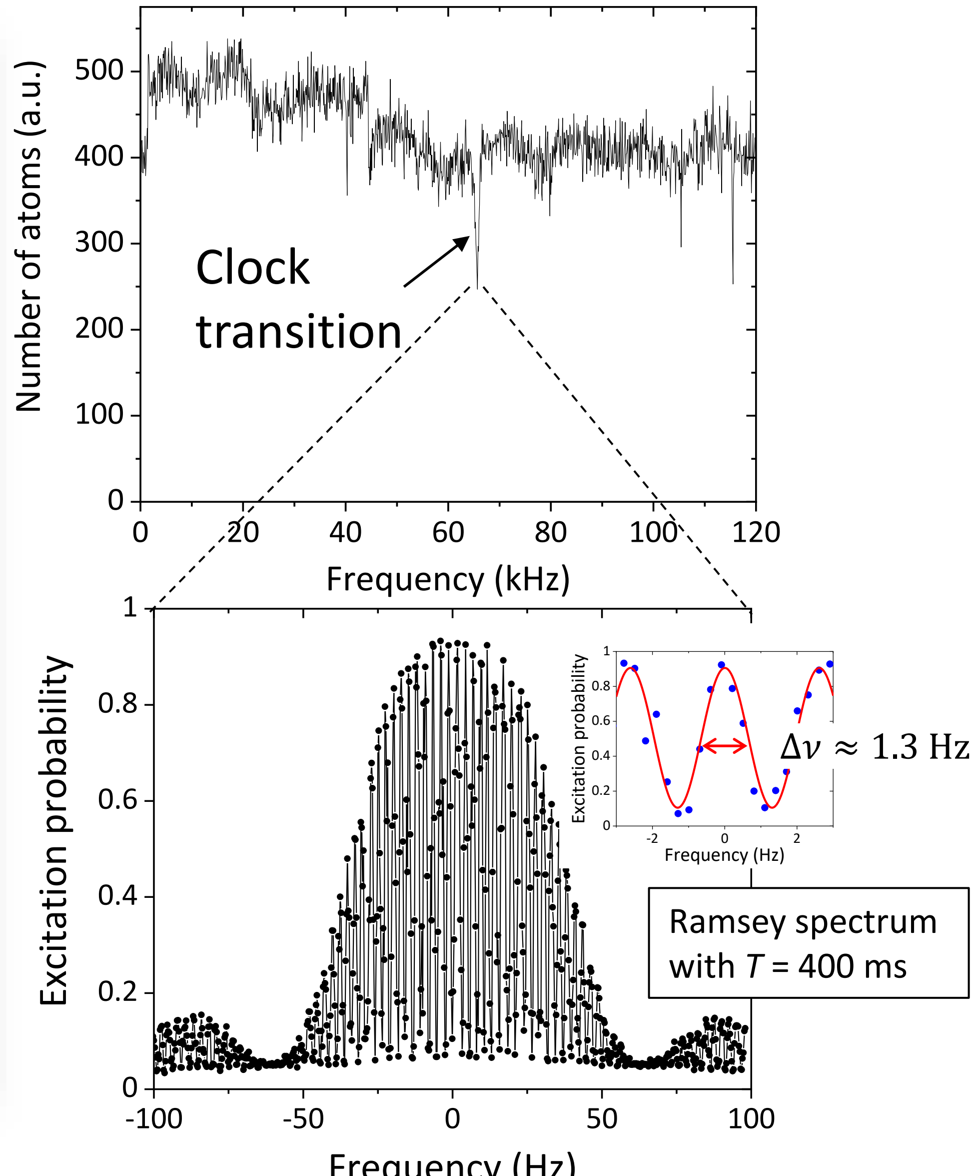
- UHV chamber for spectroscopy
- Peltier controller for BBR shield
- Sequencer, PC, etc.

Rack #3

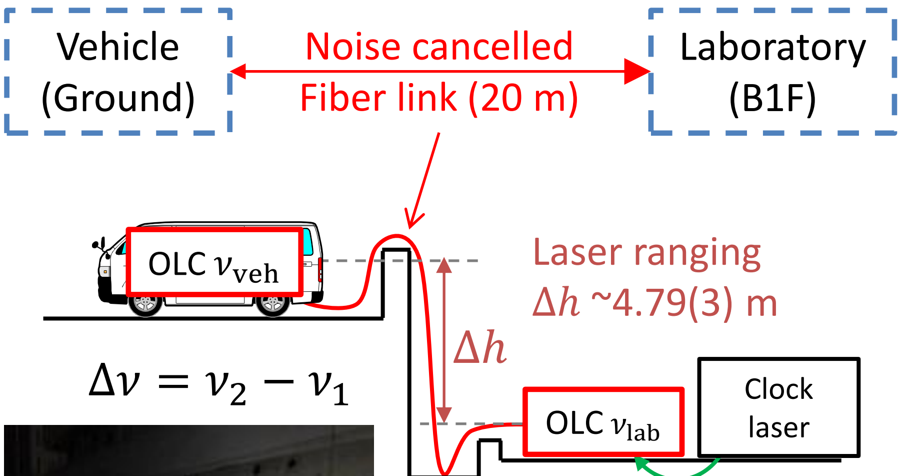
- Laser sources for atom cooling （Cooling 461 nm, 496 nm, 679 nm）
- Clock transfer laser and cavity （Clock ($2\lambda_c$) : 1.4 μm）

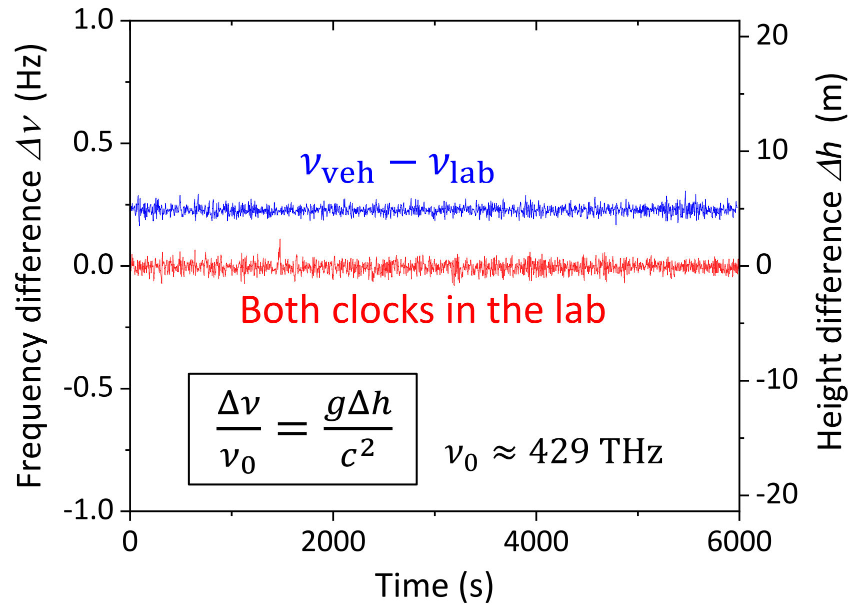
Clock operation and spectroscopy in vehicle

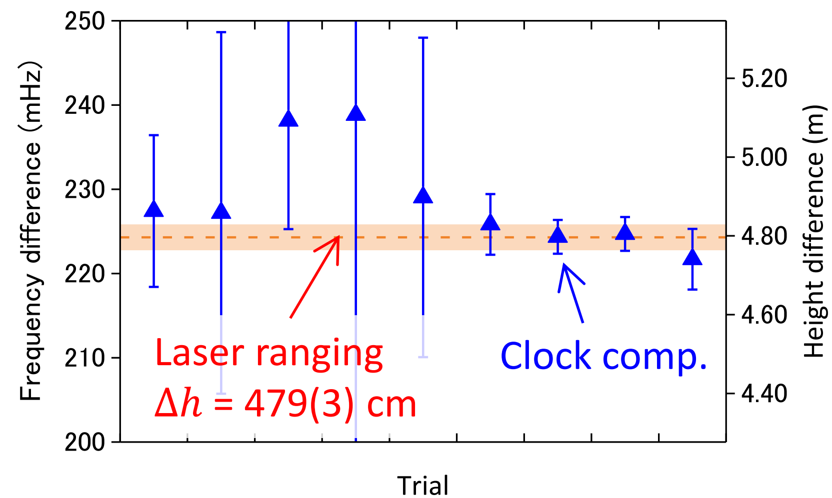




Frequency comparison between on-vehicle clock and laboratory clock







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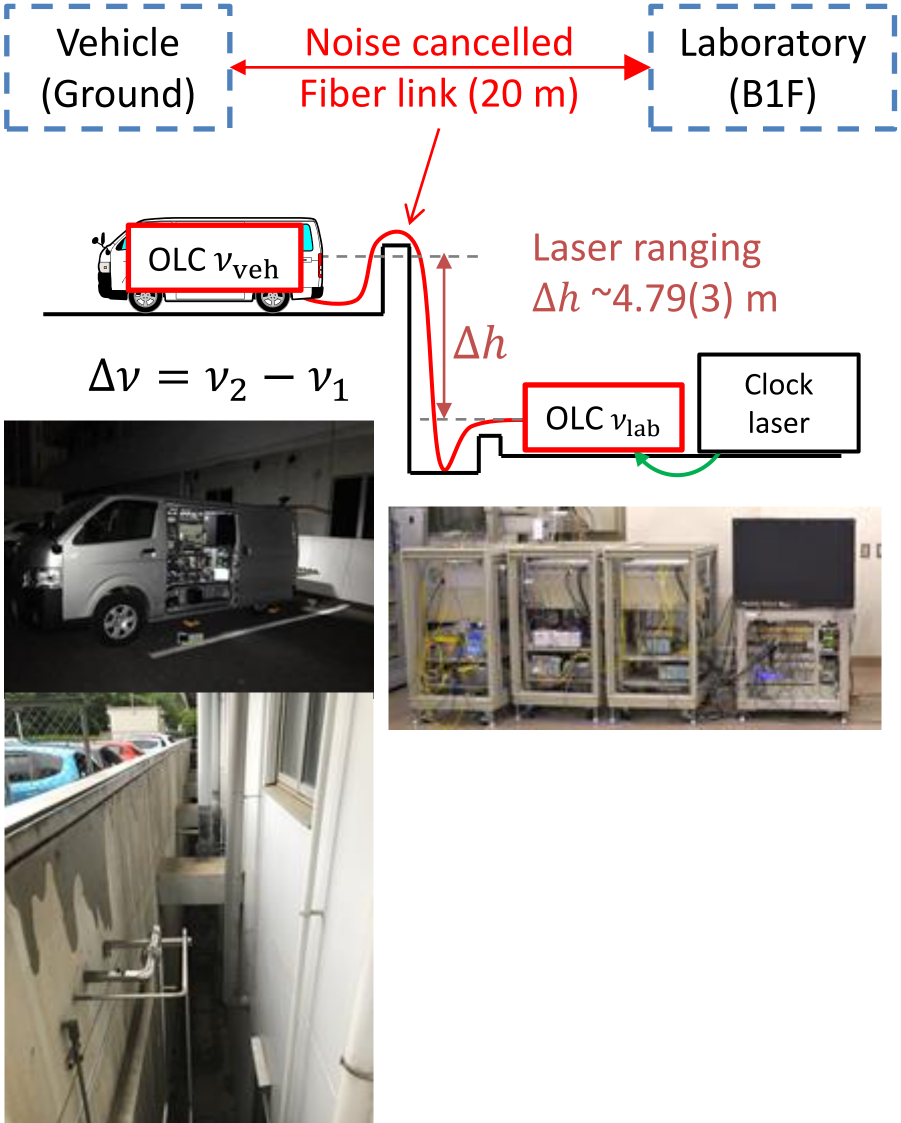
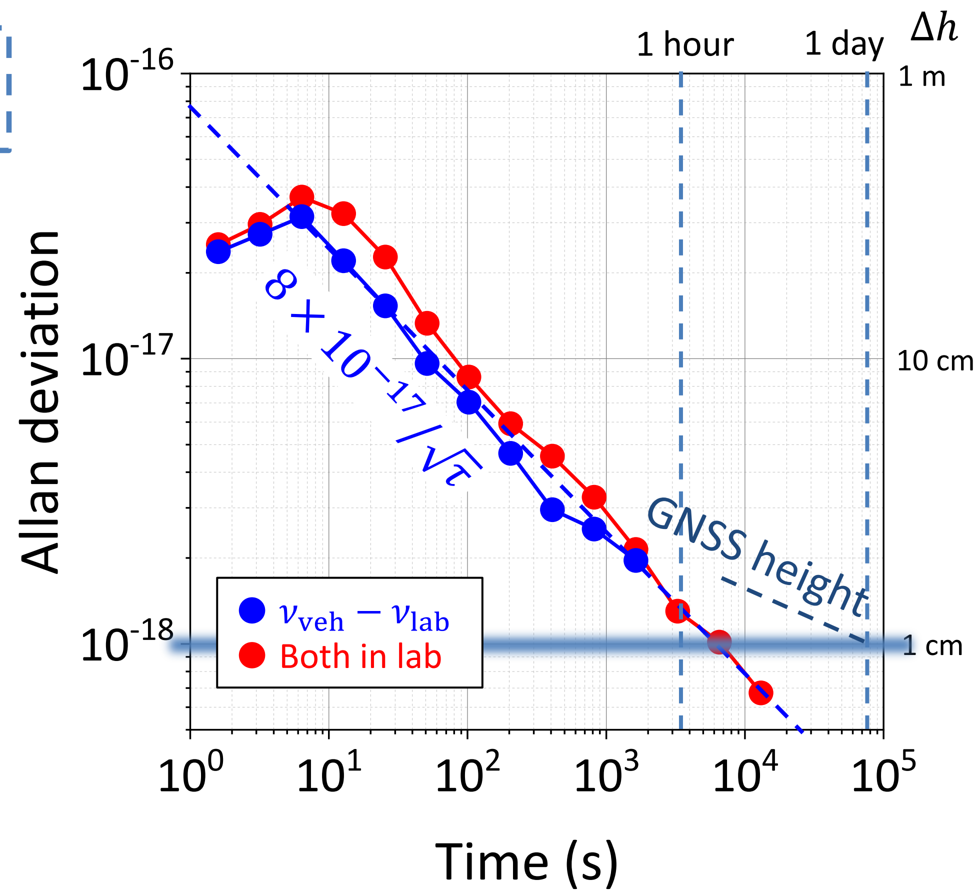


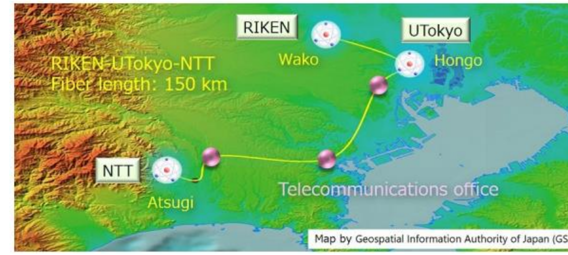


$$\sigma_y(\tau) \approx 8 \times 10^{-17}/\sqrt{\tau}$$

$$\rightarrow \sigma_{\Delta h}(\tau) \approx \mathbf{80\ cm}/\sqrt{\tau}$$

Transportable clocks with long-distance fiber link

- Long distance fiber link from Tokyo to Tohoku area (in preparation by NTT, telecom company)
  - Fiber link from Wako (RIKEN) / Hongo (UT) to Mizusawa-Esashi (VLBI astronomical observatory)
  - Distance: 500 km, fiber length: 800 km
- Transport on-vehicle clock and compare with reference clock (in RIKEN/UT) using a long-distance fiber link
- Measure gravitational potential variation for geodetic applications



ref. T. Akatsuka et al., Opt. Exp. 28, 9186 (2020)

Summary

- **Test of general relativity in TOKYO SKYTREE**
  - Demonstrate robust and stable operation of optical lattice clocks with an uncertainty of 10^{-18} outside laboratory
  - By comparing clocks at 0 m and 450 m with an uncertainty of 10^{-18}, general relativity was verified with 5 digits accuracy
- **Development of an on-vehicle optical lattice clock**
  - Frequency comparison with a laboratory clock measured the height difference with cm-precision in a few hours of averaging
  - Future applications of on-vehicle clock to relativistic geodesy with a long-distance fiber link