Development of Optical Frequency Standards and Verification of Their Equivalence Over Long Distance

National Institute for Information and Communications Technology (NICT)

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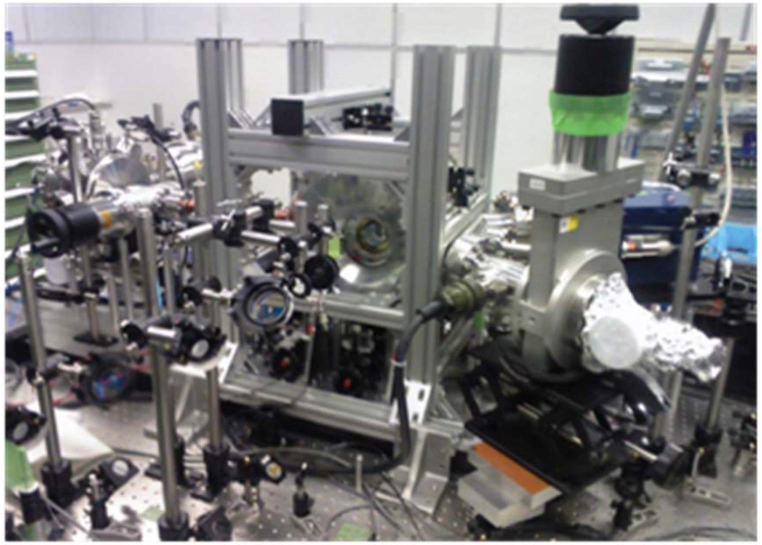
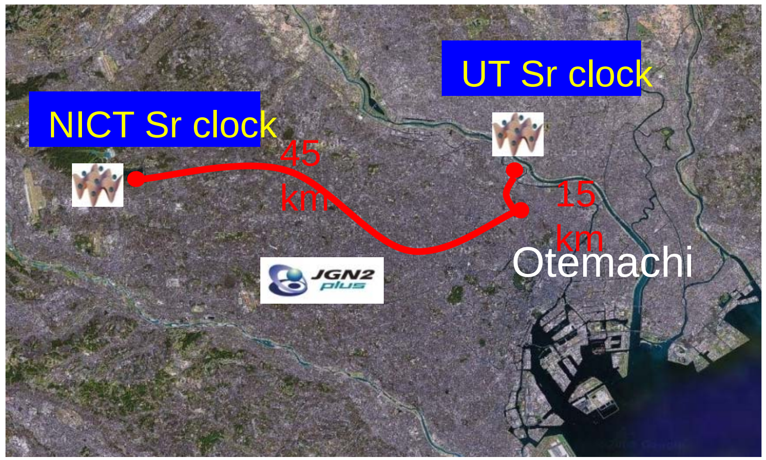
- Improvement of ^{87}Sr lattice clock at NICT
- Absolute frequency measurement through TAI (International Atomic Time)
- Direct frequency comparison between UT and NICT over optical fiber link
- Summary and future plan



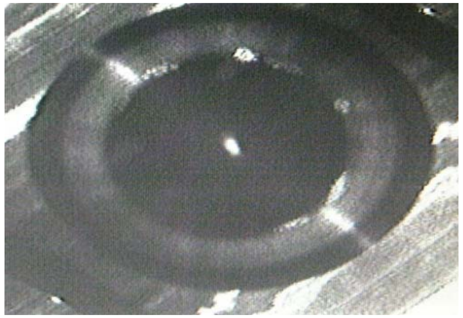
^{87}Sr lattice clock



UT-NICT fiber link

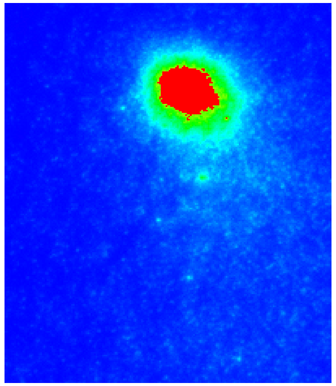
Sr lattice clock @ NICT

Blue MOT
(1st cooling)



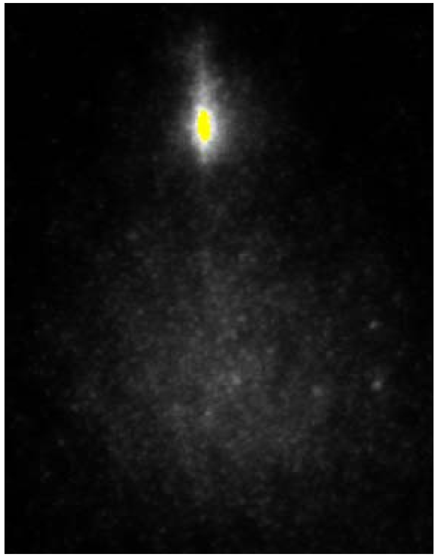
***N* ~ 3 x 10^5**
***T* ~ 2 mK**

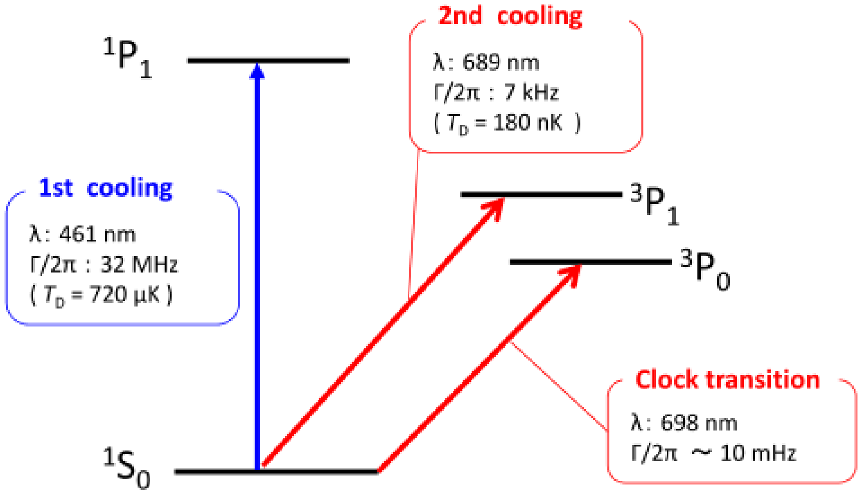
Red MOT
(2nd cooling)

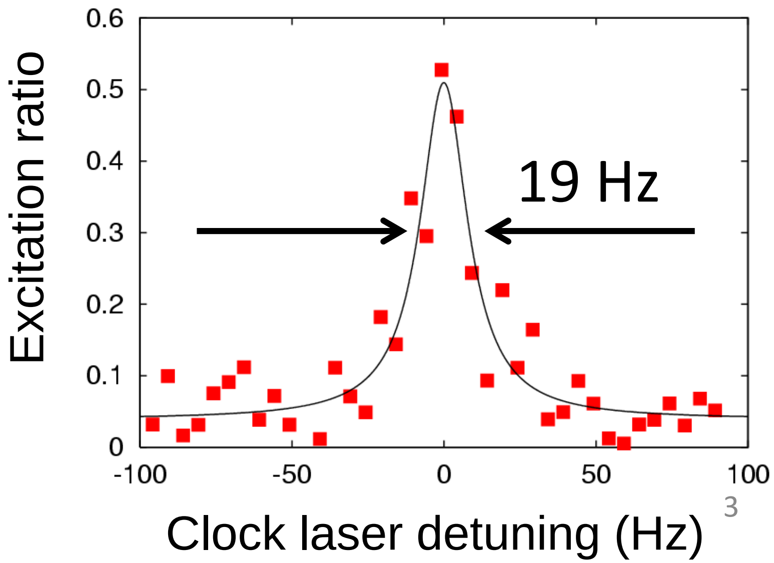


***N* ~ 5 x 10^4**
***T* ~ 3 μK**

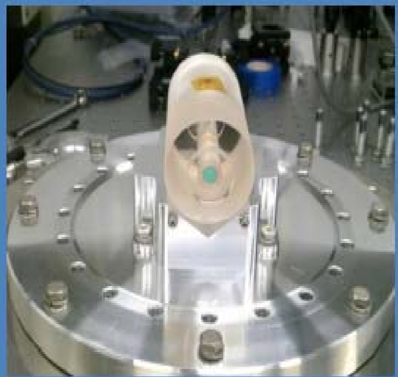
1D Lattice







“Tentative” clock laser for lattice clock



Finesse :200,000
(measured by cavity ring down method)

Length: 10cm (FSR = 1.5 GHz)

Temperature fluctuation:
< ±500μK (1 day) @~28℃

Frequency drift: 0.1~0.3 Hz/sec

Vacuum: ~10^{-8} Torr

Long cavity such as 30cm length or cold (T=120K) cavity will be standard in a few years.

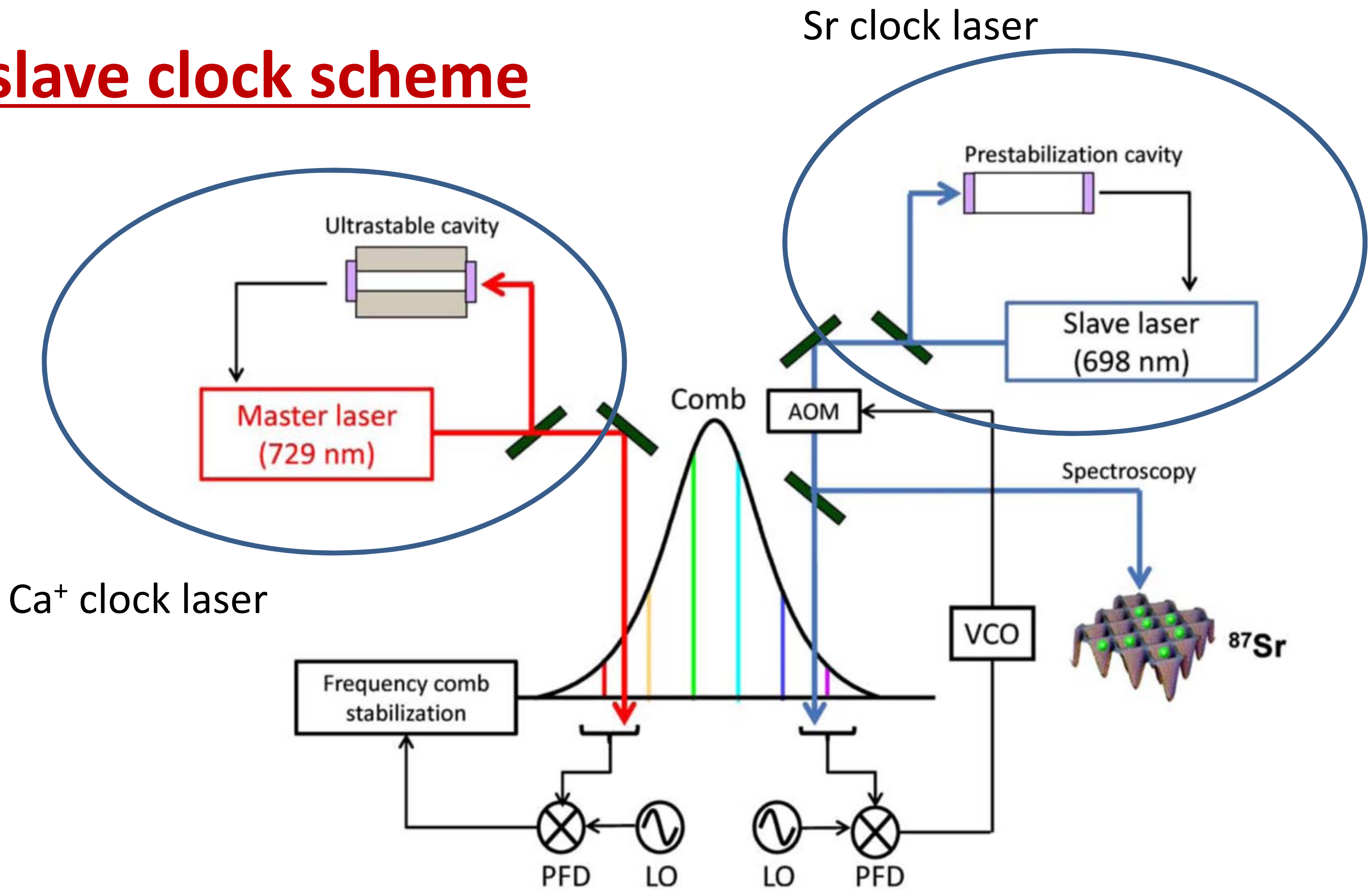
For a moment, we used simple cylindrical cavity of 10cm length, which is the cheapest ULE cavity.

Short term instability: 5e-15

(limited by seismic noise)

Instead, at this point, clock laser for Ca^+ clock has better instability of 2e-15@1s in NICT.
Different way of holding the cavity has reduced vibration sensitivity

Master – slave clock scheme

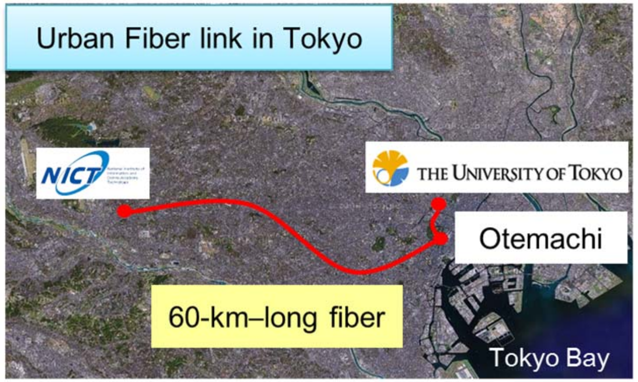


Slow excursion (0.1-2Hz) of cavity resonance was canceled by referring the Ca^+ clock laser.

Possible future application

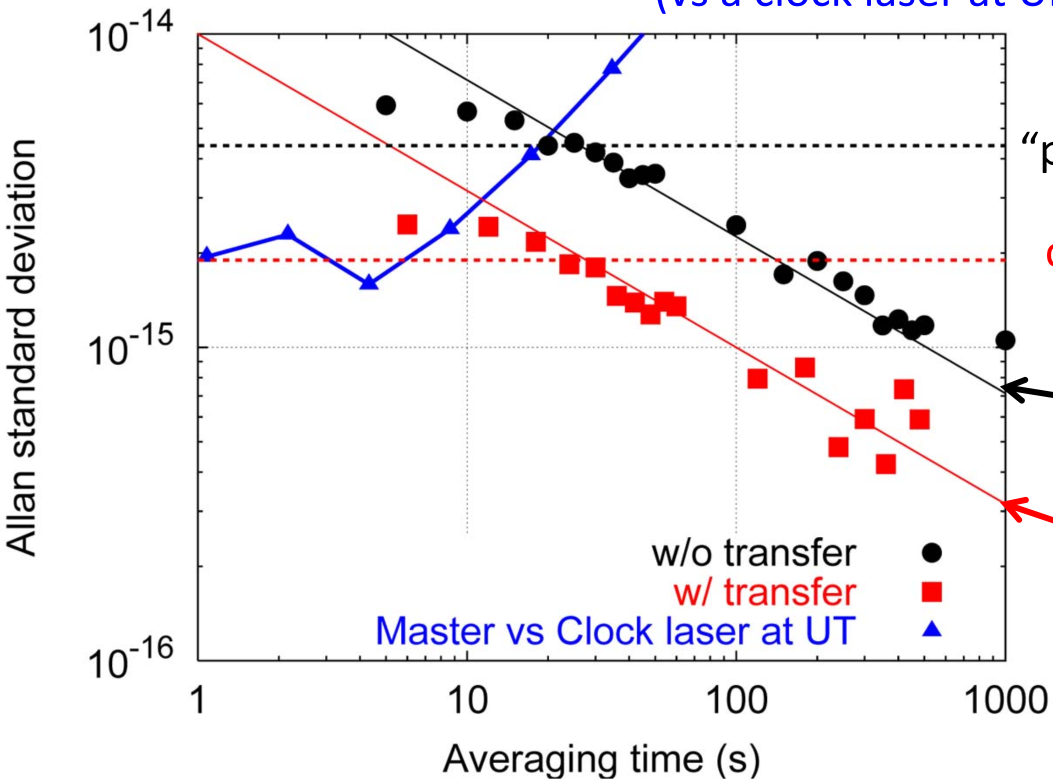
- One “super-good cavity” for multiple optical clocks in T&F institute
- cold cavity made of silicon in IR → visible wavelength of atomic clock transitions

Stability of good clock laser transferred to another clock laser



Google map

Ca^+ clock laser
(vs a clock laser at Univ. of Tokyo)



“primitive” Sr clock laser

clock laser for Ca^+

Sr clock

Sr clock
with Ca^+ laser
& comb

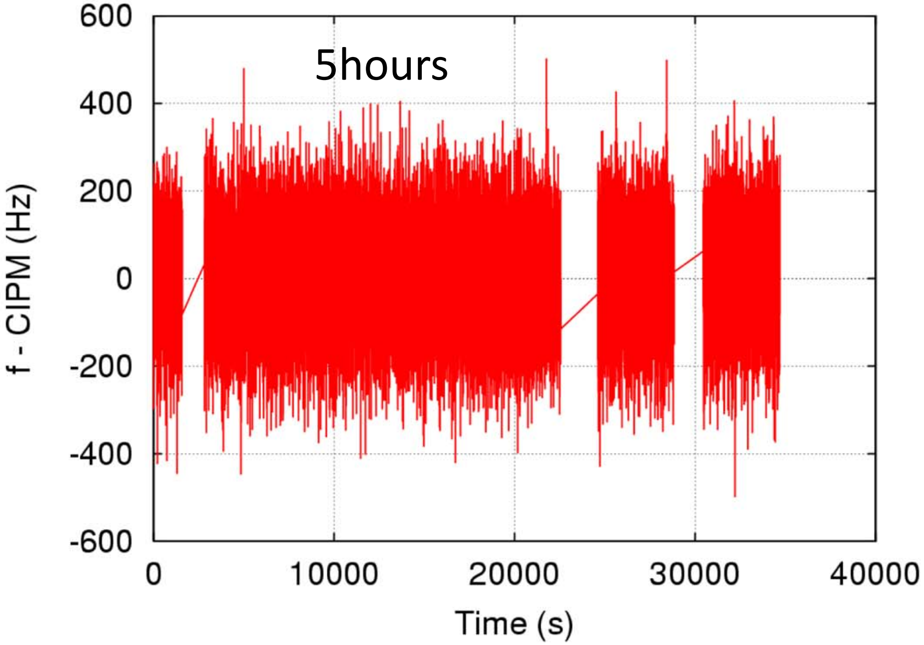
X4 reduction
in measurement
time

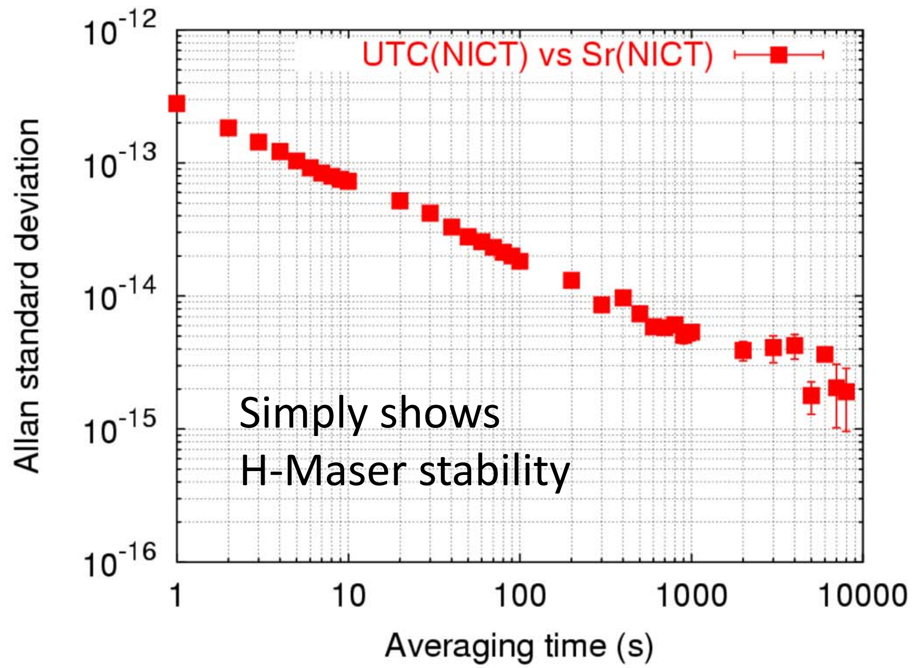
Evaluation of systematic uncertainty

Contributor	Correction (10^{-16})	Uncertainty (10^{-16})
AC Stark (lattice)	2	2
AC Stark (probe)	0.2	0.2
Collision	-0.9	3
Blackbody radiation	53	2
2^{nd} zeeman	5	2
Gravity	-83	1
Servo error	0	0.5
Total	-24	5

Total Systematic uncertainty: 5×10^{-16}

Absolute frequency measurement

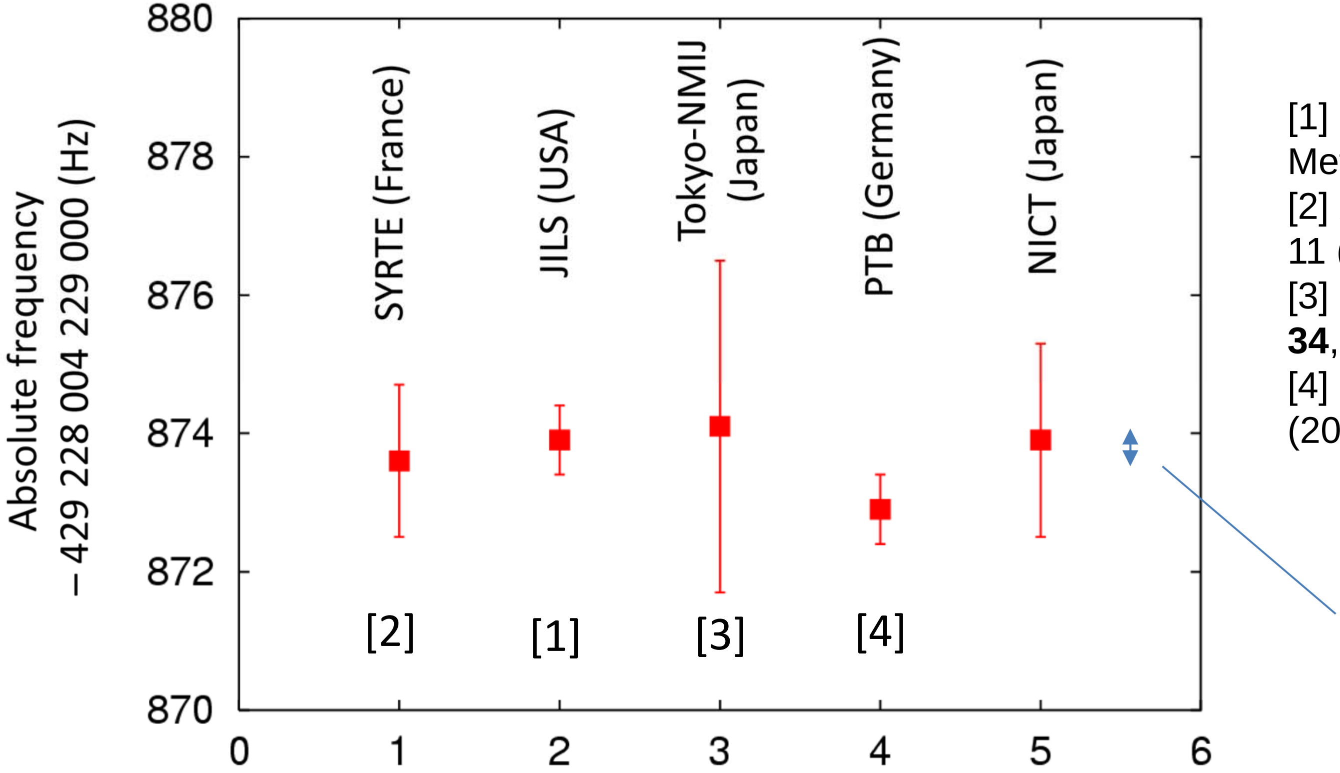




CIPM: Frequency recommended by BIPM
based on the frequencies measured by UT, JILA, and SYRTE

429 228 004 229 873.9 (1.4) Hz

Absolute frequency measured in NICT



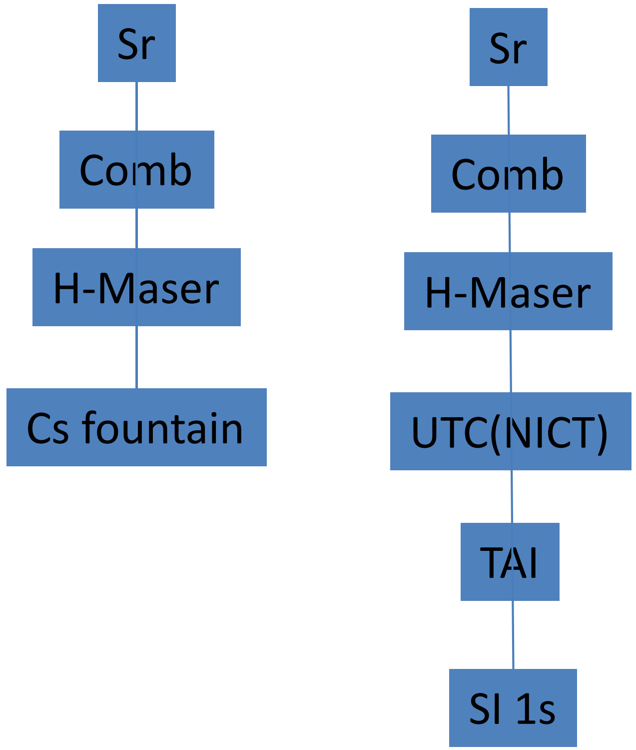
1×10^{-15}

[1] G. K. Campbell, *et al*., Metrologia **45**, 539 (2008).
[2] X. Baillard, *et al*., EPJD **48**, 11 (2008).
[3] F. L. Hong, *et al*., Opt. Lett. **34**, 692 (2009).
[4] St. Falke, arXiv:1104.4850v1 (2011).

Sr lattice clocks are accurate in 10^{-16} level.
As far as we express in “Hz”, however, the comparison never reaches 10^{-16} level

Hard wall at 1×10^{-15} in Cs-based frequency comparison

	PTB (10^{-16})	NICT (10^{-16})
Sr	1.5	5
H-Maser—Sr	5.7	17
Cs fountain —H-Maser	4.3	
fountain	7.6	(14)
UTC(X) —H-Maser		26
TAI-UTC(X)		9.8
SI 1s — TAI		4
Total	10.5	33.2

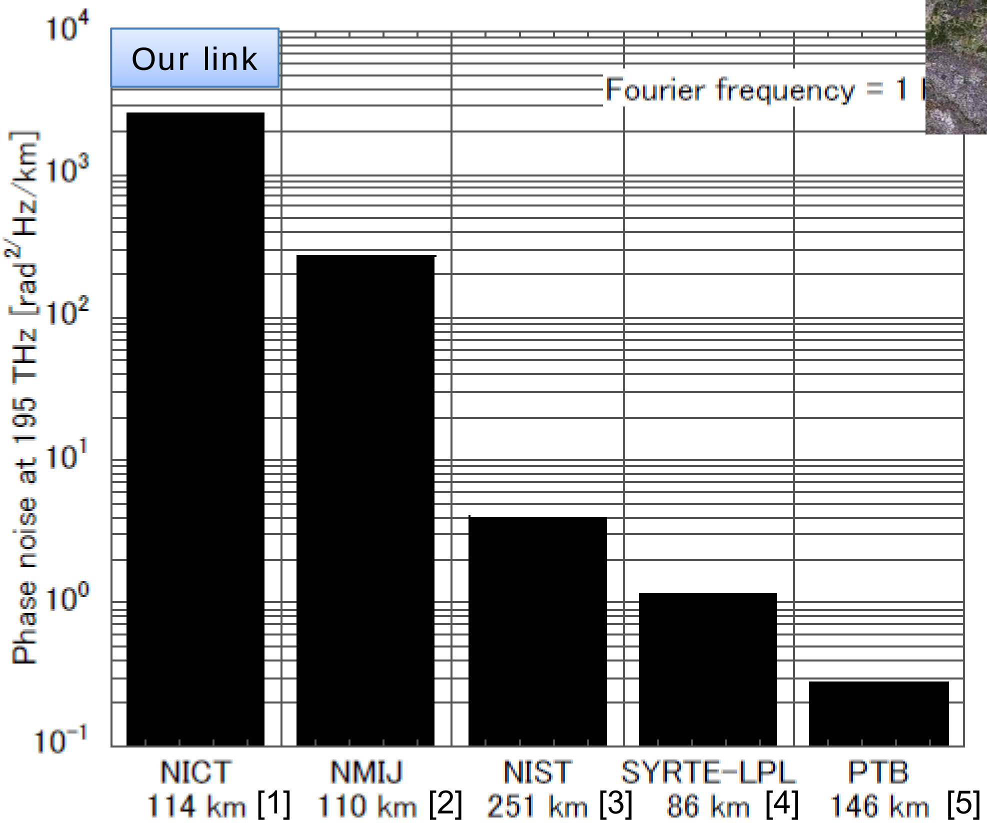


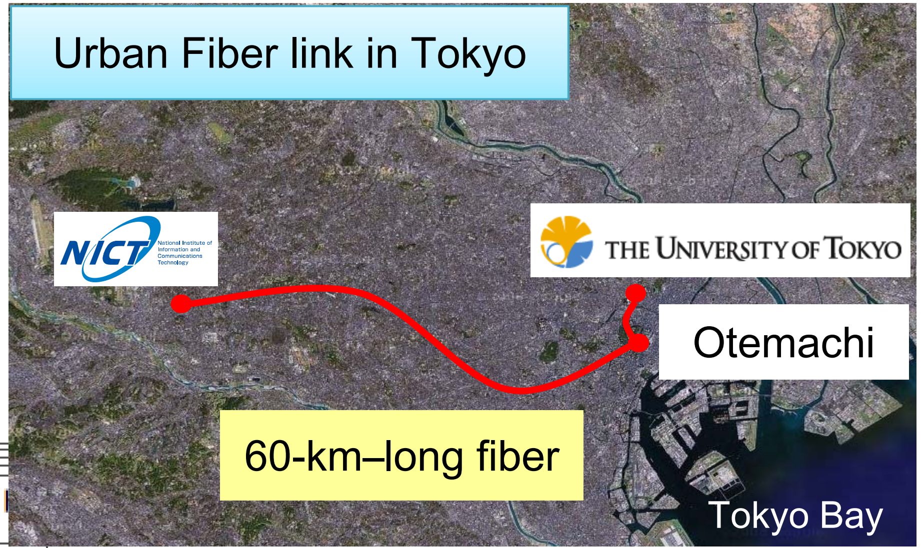
Cs fountain in NICT with accuracy of 1.4×10^{-15} was unfortunately in renovation…
→Instead, frequency link to International Atomic Time (TAI) via Japan Standard Time was used as the reference

Fiber link of clocks located at NICT and UT

[1] M. Kumagai *et al.*, Opt. Let. **34**, 19, 2949 (2009).
[2] M. Musha *et al.*, Opt. Exp. **16**, 21, 16459 (2008).
[3] N. Newbury *et al.*, Opt. Let. **32**, 21, 3056 (2007).
[4] H. Jiang *et al.*, J. Opt. Soc. Am. B **25**,12,2029 (2008).
[5] G. Grosche *et al.*, Opt. Lett. **34**, 2270 (2009).

Phase noise per km





Google map

Much larger amount of phase noise

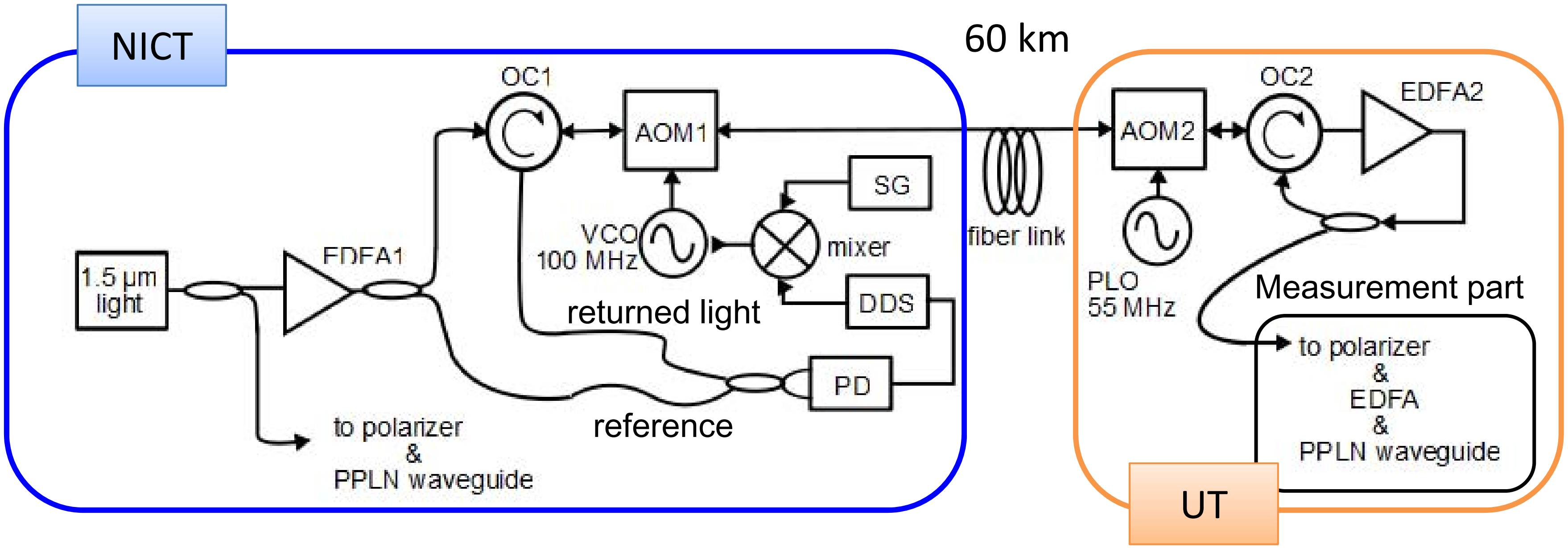
Probably due to

(1) Almost half of the link is buried along a subway line

(2) About one third of the link is wired in the air

Almost of the link noise comes from NICT-Otemachi part

Optical carrier transfer using a fiber link



Transfer system based on a fiber interferometer

- Double fiber noises, 2φ, canceled at the local site
  φ = 0 at the remote site

L. S. Ma *et al.*, Opt. Lett. **19**, 1777 (1994).

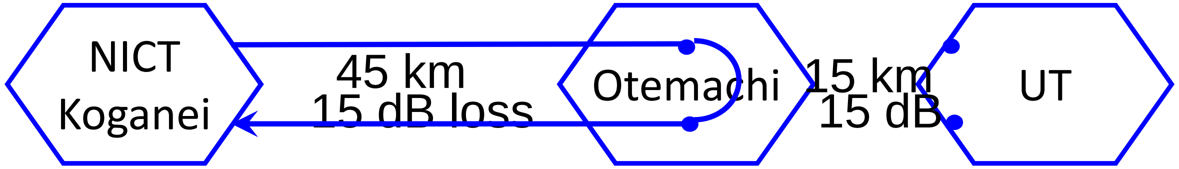
- EDFA is out of the phase-noise compensated path

➡ Remaining half of the noise does not limit the performance of our system

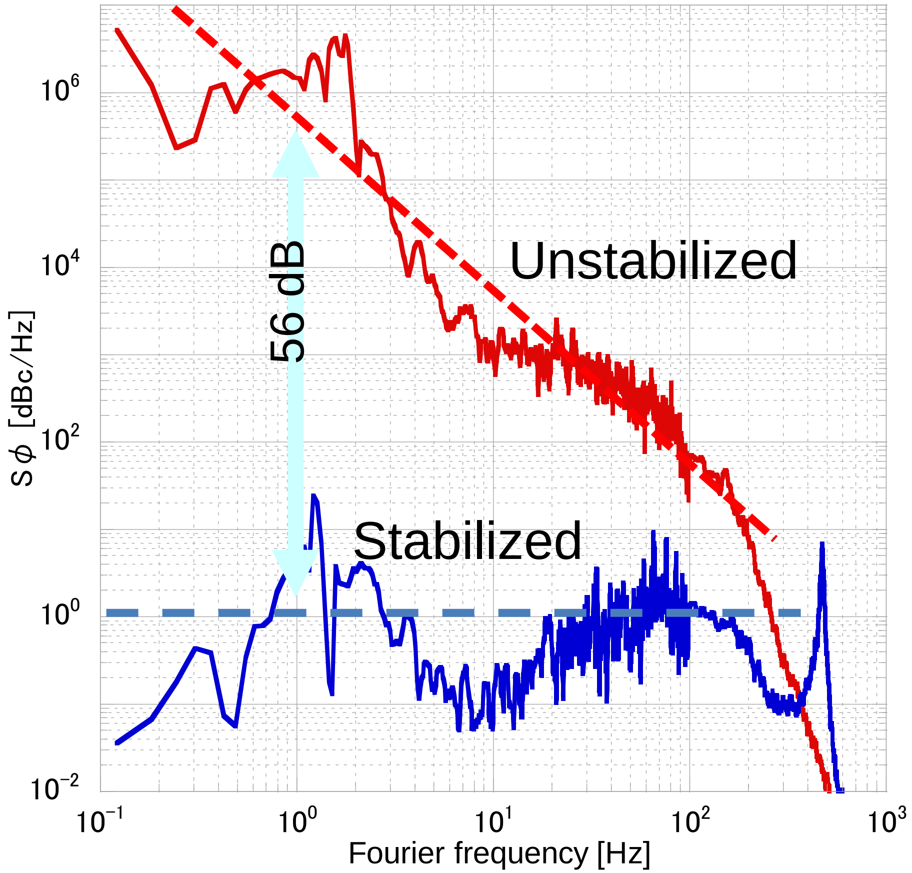
By independent measurements

M. Fujieda *et al.*, Opt. Express. **19**, 16498 (2011).

Evaluation of the fiber link

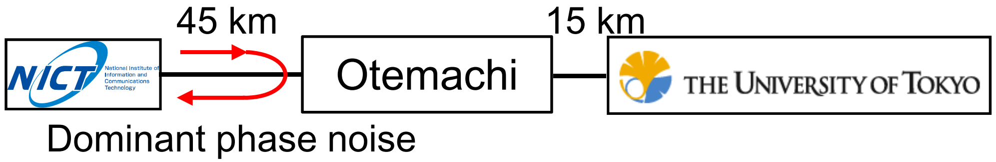


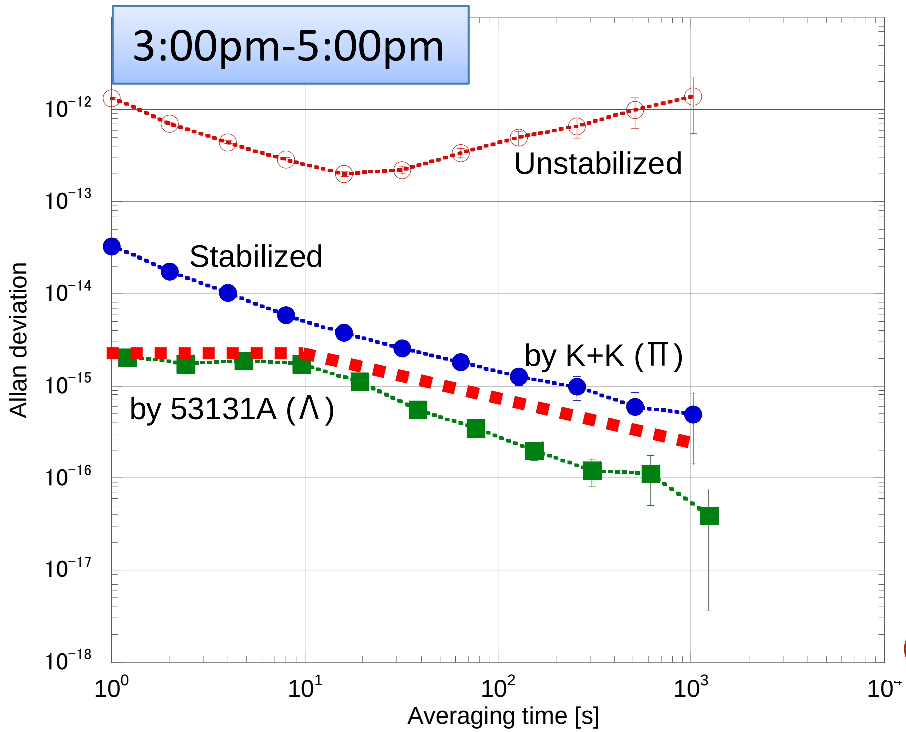
Total length: 90 km, optical loss: 30 dB

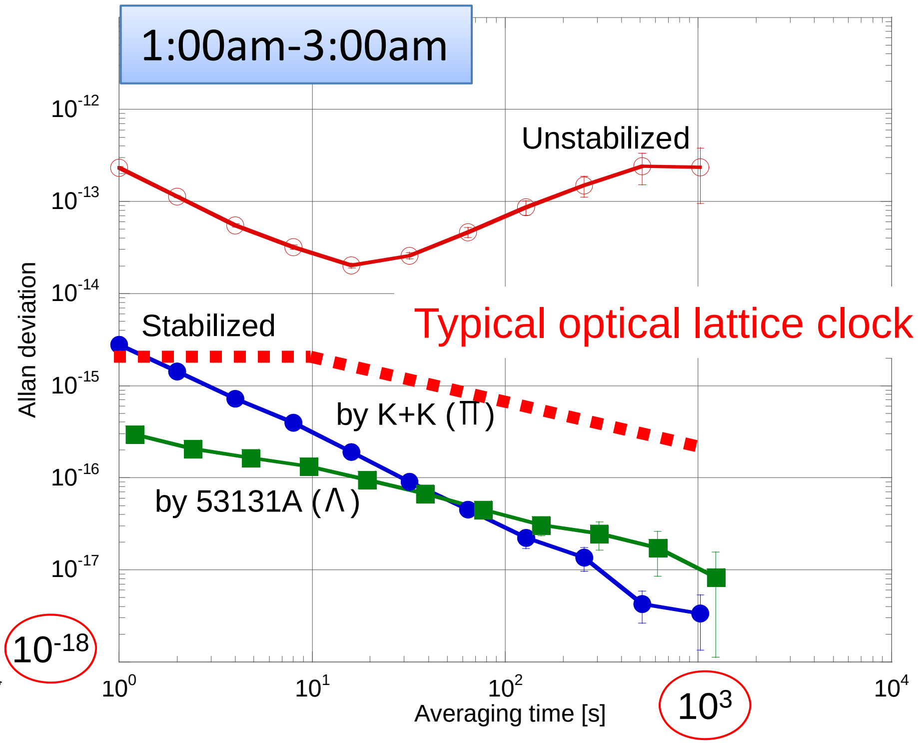


Instability of a fiber link: Day & Night

Transfer instability of out-of-loop beat
in NICT-Otemachi round-trip link







Should be done
in midnight in current circumstances

Overall system instability: 2×10^{-15} at 1s
7×10^{-17} at 1000s

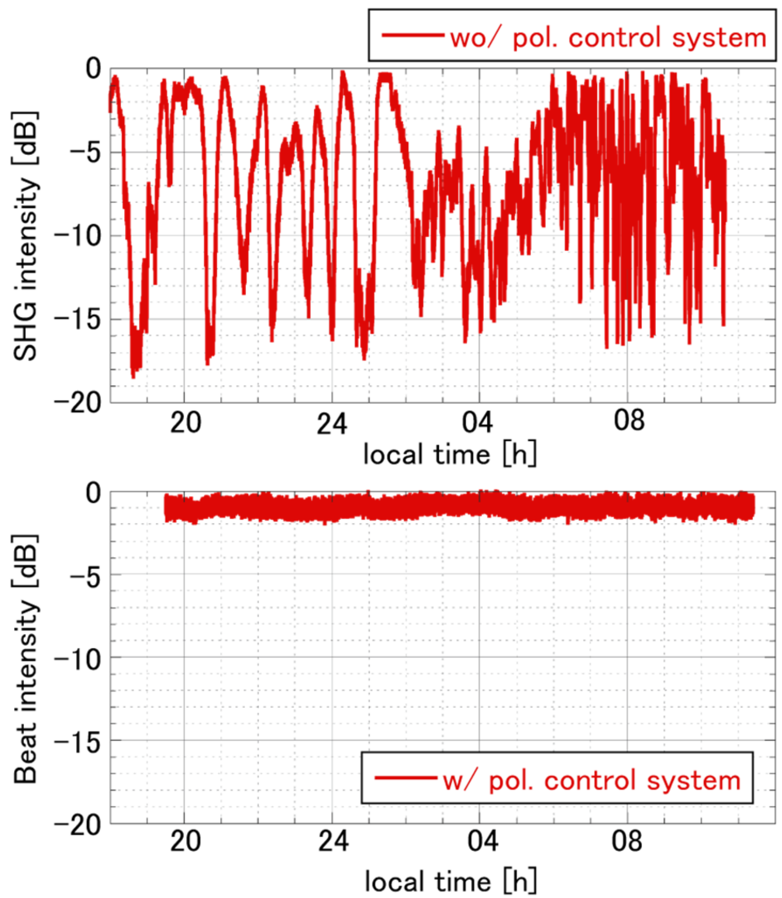
Including:
- EDFA
- waveguide PPLN
- frequency comb

Polarization stabilizer

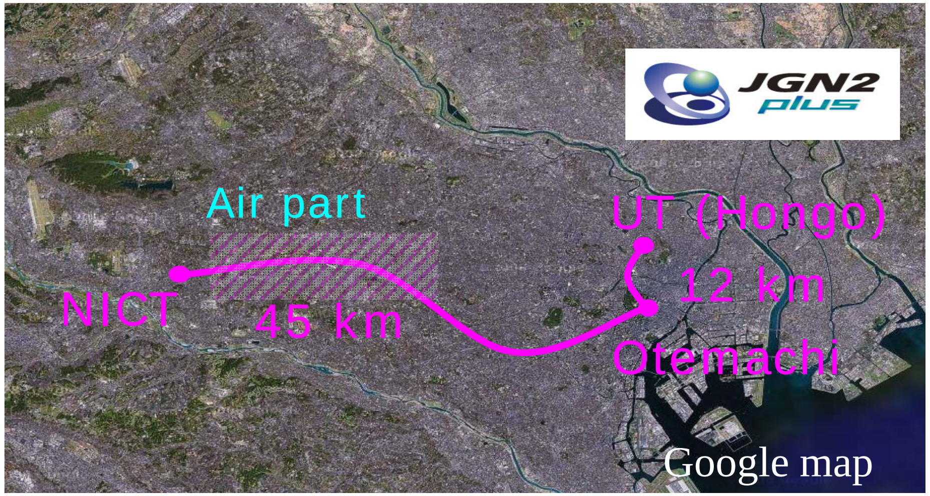
The polarization of the light varies considerably after the transmission though 60km single mode fiber

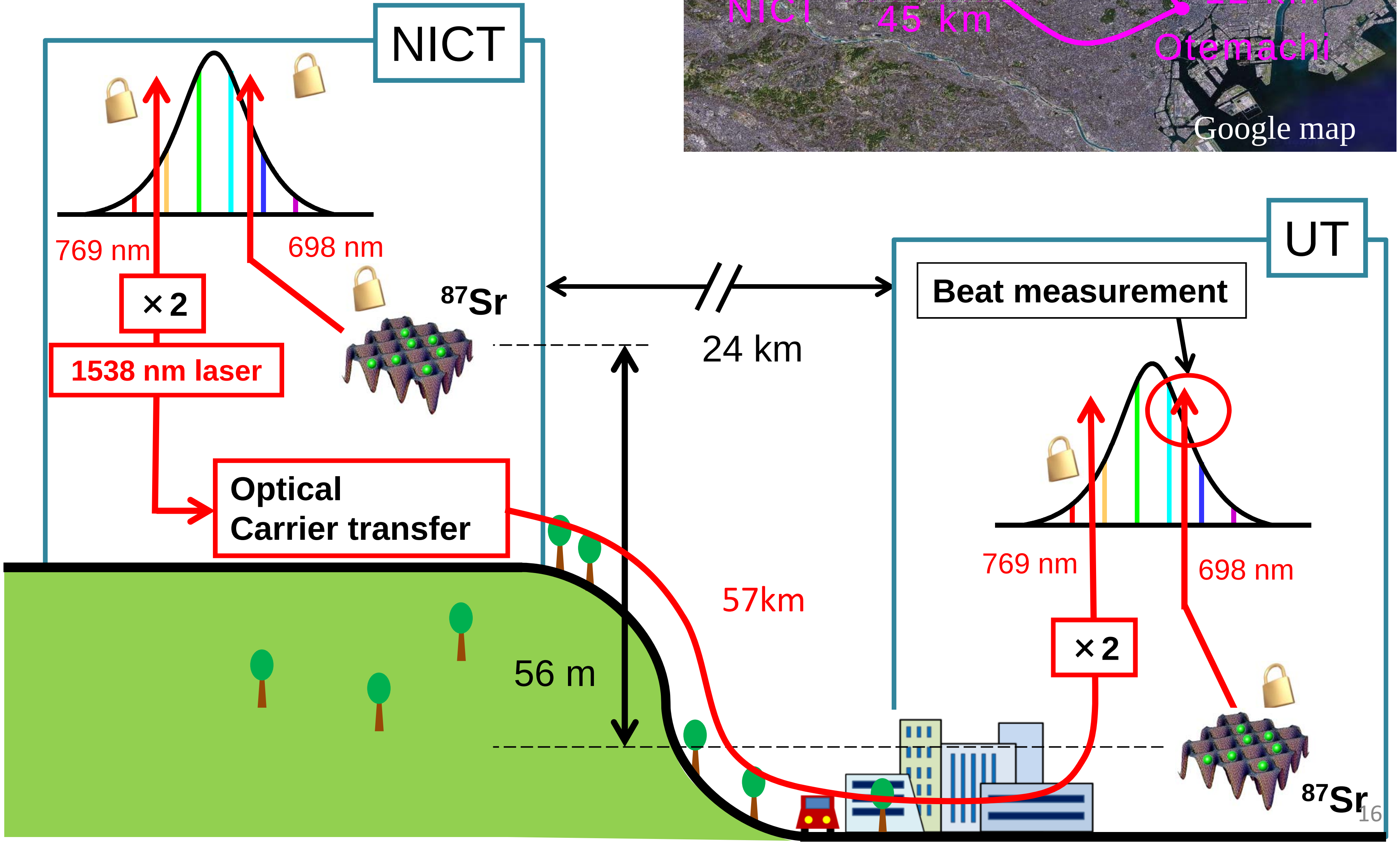
SHG is so sensitive to polarization.

→
Polarization tracker and servo control was installed for the first time to our knowledge

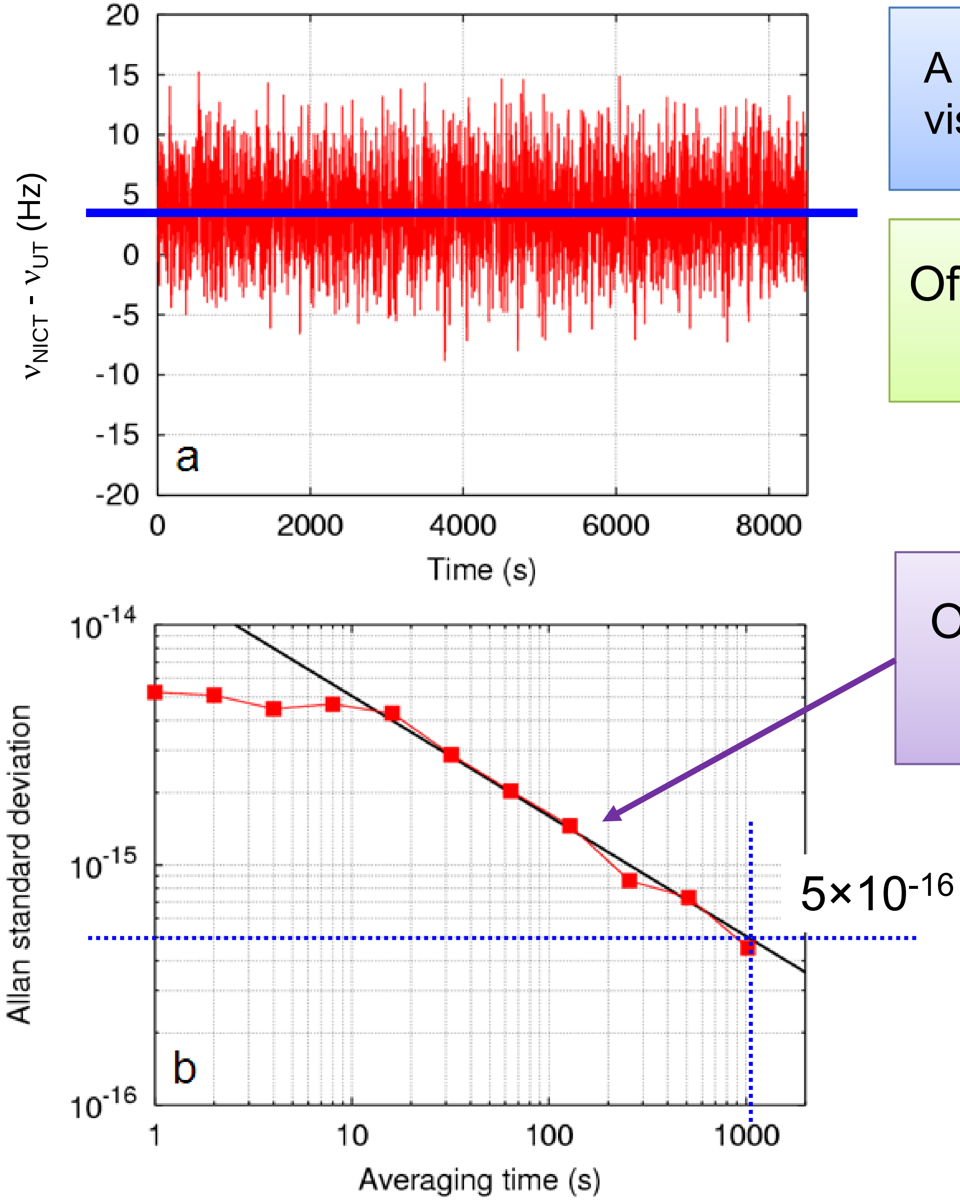


All-optical direct comparison between NICT & UT clock





Frequency difference & stability between distant Sr clocks



A Hz-level frequency difference is clearly visible over the time scale of minutes

Offset: predominantly due to differential gravity shift

Obtained instability

$1.6\times10^{-14}/\sqrt{\tau}$

consistent

Dick-effect-limited instability

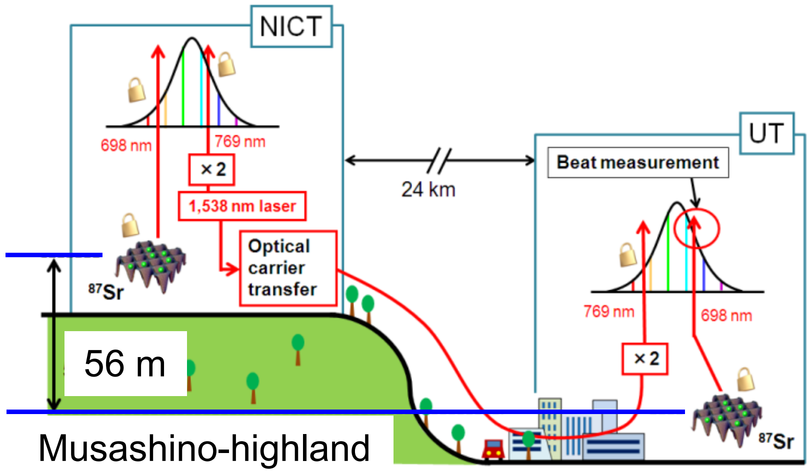
UT : $6.0\times10^{-15}/\sqrt{\tau}$

NICT : $1.5\times10^{-14}/\sqrt{\tau}$

Corrections and uncertainties at UT and NICT

	UT (Hz)		NICT (Hz)	
contributor	Correction	Uncertainty	Correction	Uncertainty
AC Stark –Lattice	0.19	0.10	0.10	0.10
AC Stark -Probe	0.00	0.00	0.01	0.01
BBR	2.17	0.10	2.26	0.10
2nd Zeeman	1.24	0.10	0.23	0.10
Gravitational shift	-0.95	0.09	-3.57	0.05
Collision	0.00	0.10	-0.04	0.12
Servo error	0.00	0.01	0.00	0.01
Total	2.65	0.22	-1.01	0.22

(Link uncertainty to SI second) (0.78)



Elevation of a lattice clock from Earth's geoid surface

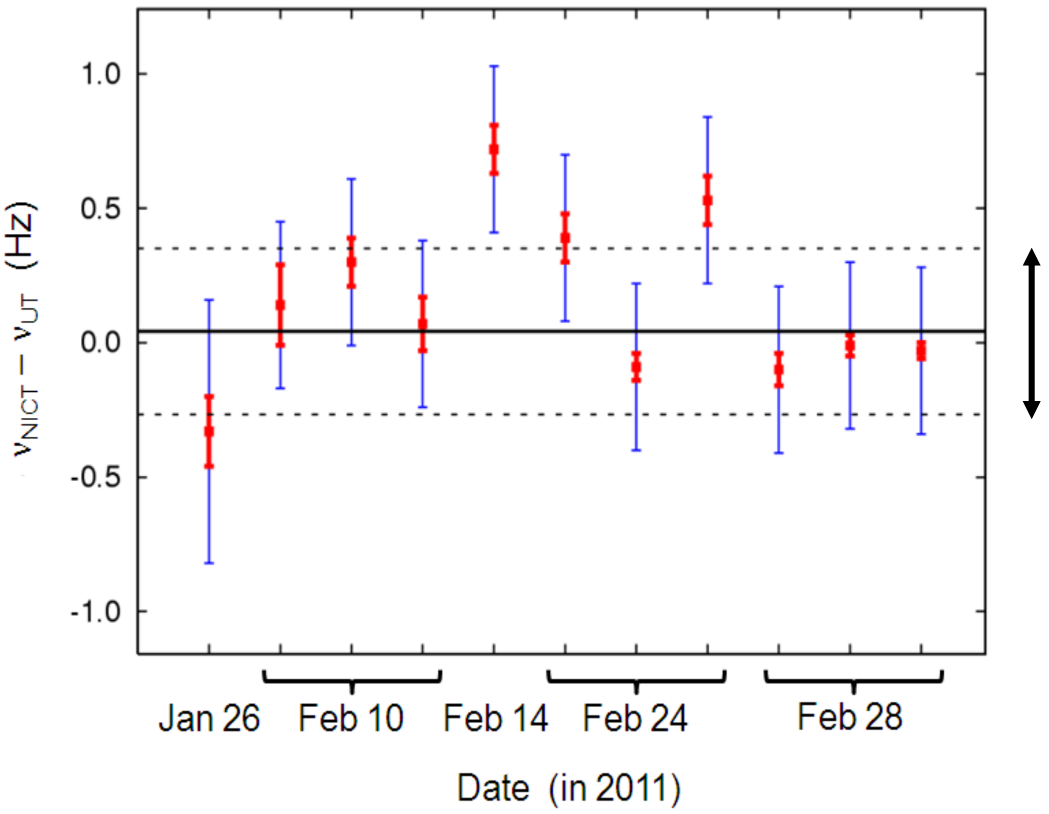
UT: 20.37 ± 2 m
NICT: 76.33 ± 1 m

Systematic shift of Frequency difference

$\nu_{NICT} - \nu_{UT}$ = 3.66 (0.31)Hz

Frequency difference between two distant Sr clocks

Frequency difference after correcting systematic frequency shift



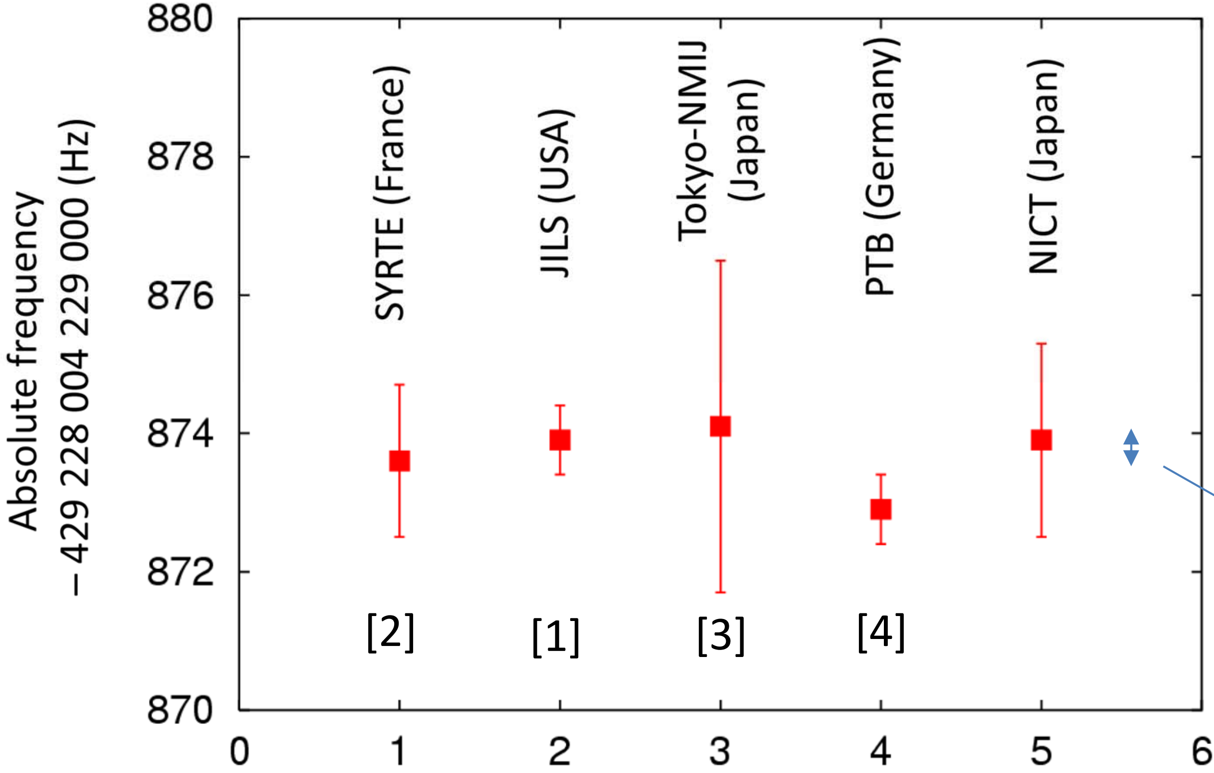
Total systematic uncertainty of two clocks (0.31Hz)

Measurement records in the range of 900-12000s

Weighted mean 0.04Hz (1.0×10^{-16}) (Solid black line in figure) < Total systematic uncertainty 0.31Hz (7.3×10^{-16}) (dashed lines in figure)

No limitation imposed by the fiber transfer

Agreement between institutes for the 1st time in 10^{-16} level !

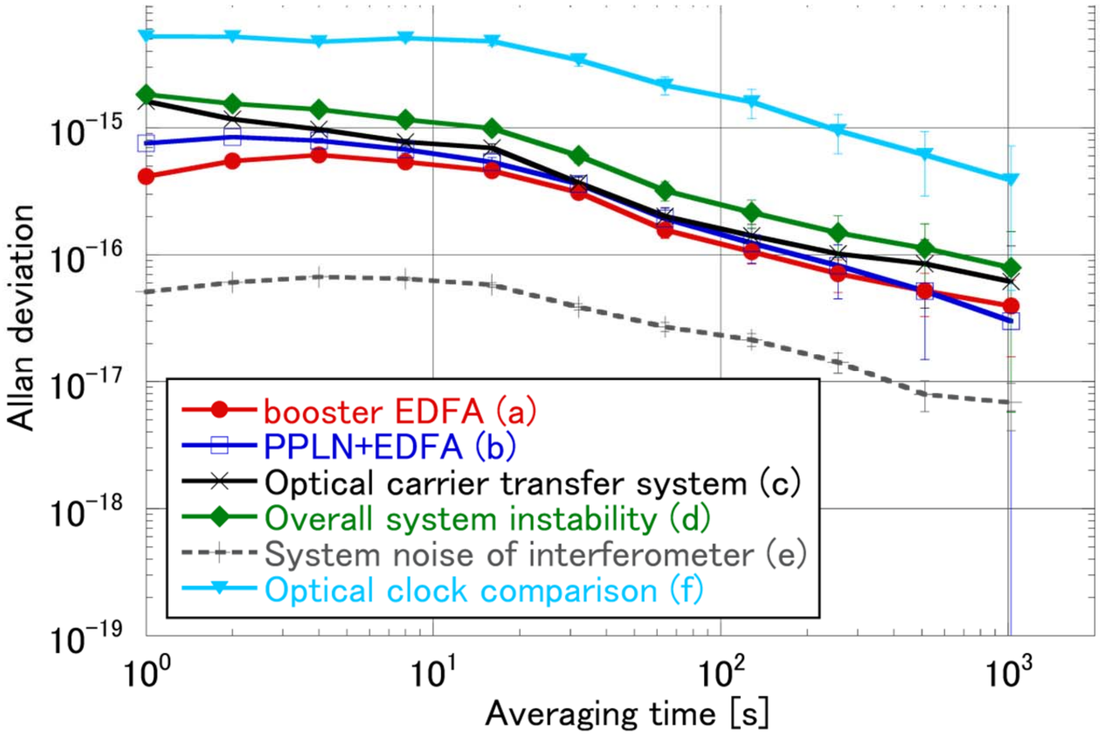


[1] G. K. Campbell, *et al.*, Metrologia **45**, 539 (2008).
[2] X. Baillard, *et al.*, EPJD **48**, 11 (2008).
[3] F. L. Hong, *et al.*, Opt. Lett. **34**, 692 (2009).
[4] St. Falke, arXiv:1104.4850v1 (2011).

1×10^{-15}

Our result shows that the agreement between NICT and UT is half of 1×10^{-15}

Next step



- Quieter fiber is mandatory for the improvement of the short-term stability
- Repeater laser should be installed in remote site instead of the amplification by a “free-run” EDFA

Time and Frequency Transfer Methods

	Uncertainty	Range	
GPS Dual Codes	700ps～500ps	Global	
GPS Carrier Phase	300ps～150ps	Global	Currently in use
TWSTFT	500ps～200ps	～5000km	
TWSTFT Dual Channel	100ps～20ps	～5000km	
TWSTFT Carrier Phase	10ps～4ps	～5000km	
VLBI	20～4ps	Global	
ACES	100～3ps	～2000km	ESA mission
Fiber Transfer	<1ps	～100km	

TWSTFT : Two-Way Satellite Time and Frequency Transfer
VLBI : Very Long Baseline Interferometry
ACES : Atomic Clock Ensemble in Space

Summary and Future Plans

^{87}Sr Lattice Clock

- Total systematic uncertainty: 5×10^{-16}
- Absolute frequency measurement through TAI : 3.3×10^{-15}

Fiber Link

- Comparison instability : $2 \times 10^{-15}/\tau$ (7×10^{-17} @1000s)
- Good agreement of UT and NICT lattice clocks within their total systematic uncertainties

Future Plans

- Fiber Link : further noise reduction
- ^{87}Sr Lattice clock
  - stabilize clock laser with 30cm long cavity
  - reduce BBR with a cryogenic chamber
- Precise frequency comparisons with foreign institutes
  - Carrier Phase method & TWSTFT (Two-Way Satellite T&F Transfer)
  - VLBI (Very Long Baseline Interferometry)
  - ACES (Accurate Clock Ensemble in Space)