Development of atomic clocks and frequency transfer techniques at three laboratories around Tokyo area

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(3) University of Tokyo and Riken

Agenda

- Background
- Report from
  - University of Tokyo and RIKEN
  - NMIJ
  - NICT
- Summary of activities in 4 institutes
- Summary

Background

Tokyo area =
One of active areas on R&D of atomic clocks

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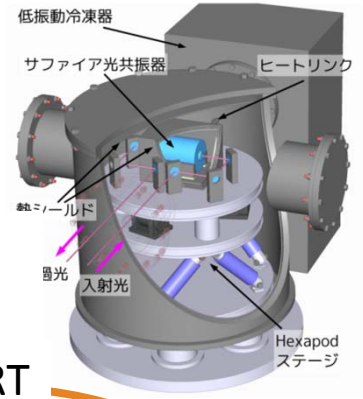
Optical Lattice Clocks, Cavities, and Fiber Link under development at UT and Riken



No Dead time operation:
highly stable clock utilizing stable L.O. (20K silicon cavity)

THE UNIVERSITY OF TOKYO

Cryogenic Sr clock @70K

Cryo-Sr@70K

Hg @RT

f_{Hg}/f_{Sr}@10^{-17}

Fiber link @10^{-17}-10^{-18}

Cryogenic Sr clock @70K

Hg clock @RT

2011.04-

RIKEN

Sync. operation to evaluate 10^{-17}-10^{-18}

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Demonstration of *N*=1000 advantage
QPN limit stability 10^{-17}@1600s

2010-2011

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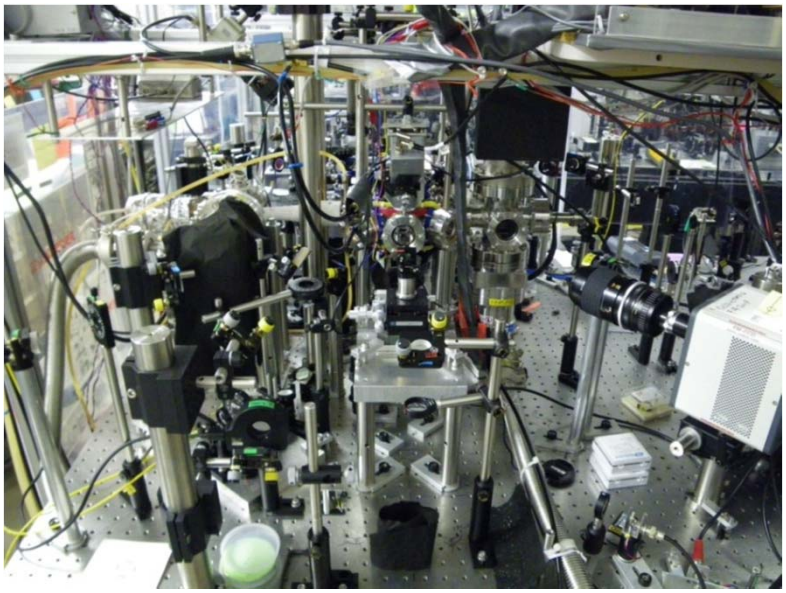
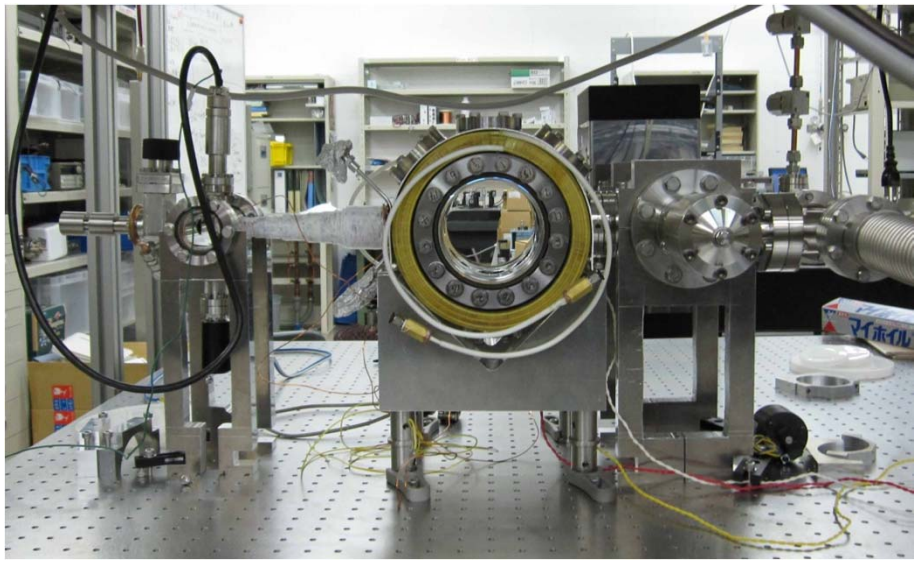
Optical lattice clocks at NMIJ

Yb optical lattice clock



Sr-Yb dual optical lattice clock



$^1S_0(F = 1/2)$-$^3P_0(F = 1/2)$ transition in ^{171}Yb

***f* = 518 295 836 590 863.1(2.0) Hz**

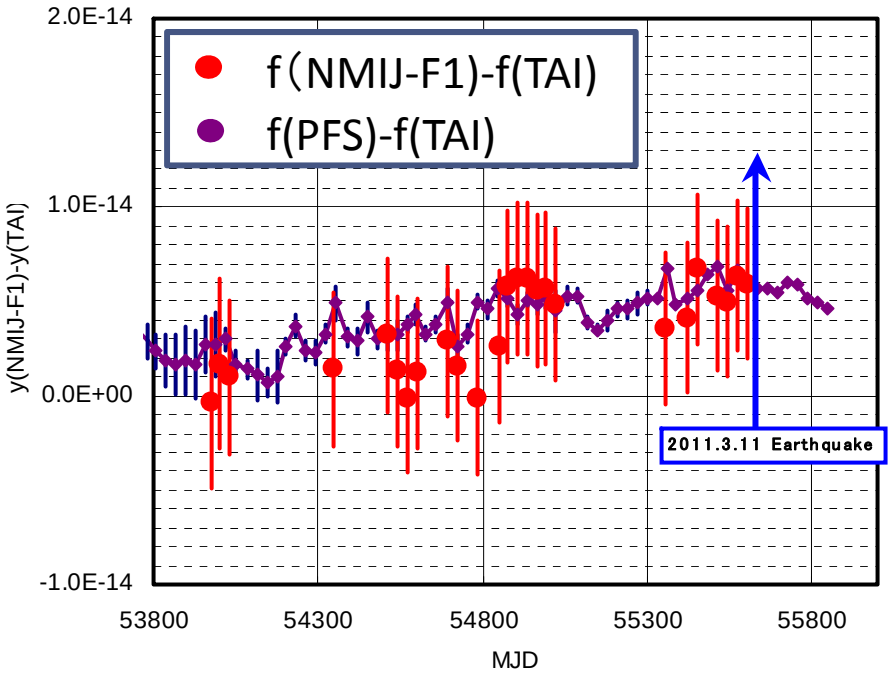
(Fractional uncertainty 3.9×10^{-15})

M. Yasuda et al., Appl. Phys. Express vol. 5, 102401, Sep. 2012.

Secondary representations of the second (Oct., 2012)

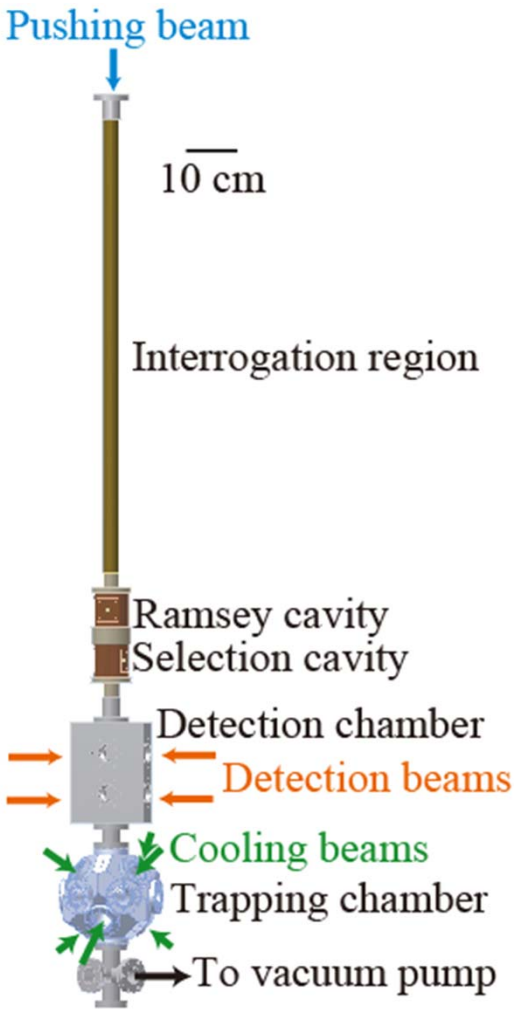
1) **Contribution to the Sr lattice clock community;**
2) **As a second optical clock to be used for the evaluation of the Yb lattice clock;**
3) **Measurement of the Sr/Yb frequency ratio with an uncertainty beyond the Cs limit;**
4) **Contribution to the experimental demonstration of alpha variation.**

Atomic fountains at NMIJ



Calibration of TAI using NMIJ-F1

- **25 reports to BIPM in recent 4 years until Feb.2011.**
- **The operation has stopped since March 2011 (Earthquake).**
- **We will need some time for recovery.**

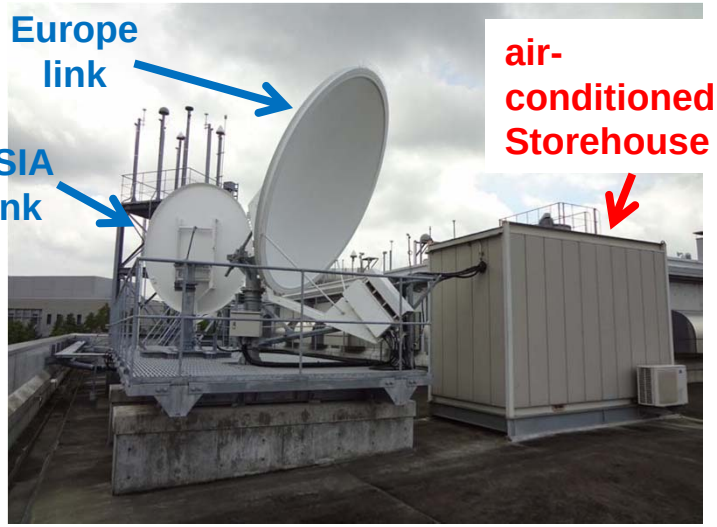


NMIJ-F2 (under construction)

UTC(NMIJ) generation system and time transfer link at NMIJ

Temperature controlled chambers for 5071A

CH1-75A



Earth station configuration

- UTC(NMIJ) is generated by reference signal form one H-maser steered by an AOG.
- Clocks at NMIJ
  - 4 H-masers
    - 1 RH401A made by Anritsu
    - 1 SD1T01A made by Anritu
    - 1 CH1-75A made by KVARZ
    - 1 VCH-1003M made by VREMYA
  - 3-5 Cs clocks
    - 5071A with high performance beam tube
- Time Transfer Link
  - UTC PPP (GPS carrier phase) using Z12-T: main time transfer tool
  - TWSTFT : backup tool

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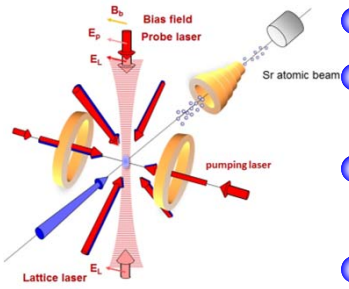
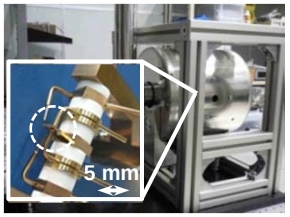
Atomic clocks at NICT

1D optical lattice clock with spin-polarized ^{87}Sr atoms



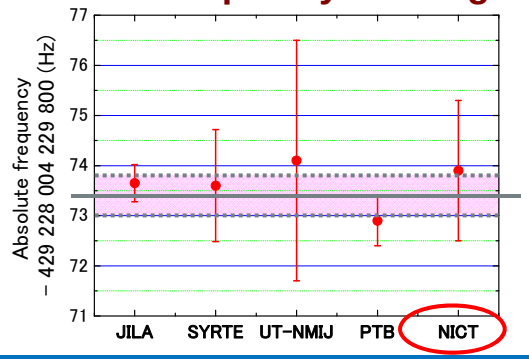
- Systematic uncertainty: 5e-16
- Contribution to secondary representation of the second
- Direct frequency comparison with Univ.Tokyo using fiber link
- Operating Freq. ref. at NICT

$^{40}Ca^{+}$ single-ion optical clock

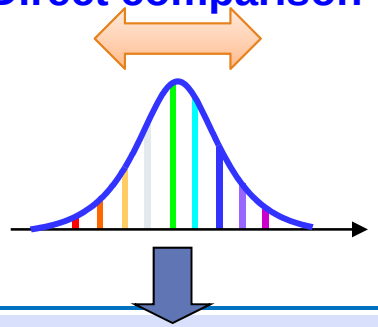


- Systematic uncertainty: 2e-15
- Contribution to CIPM Recommend
- Comparison with WIPM in China by GPS link
- Ref. for In^{+}-Ca^{+} clock development

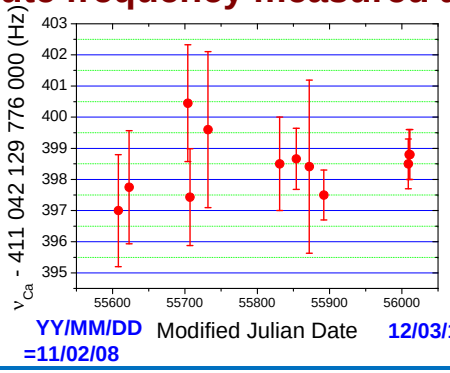
Absolute frequency in five groups



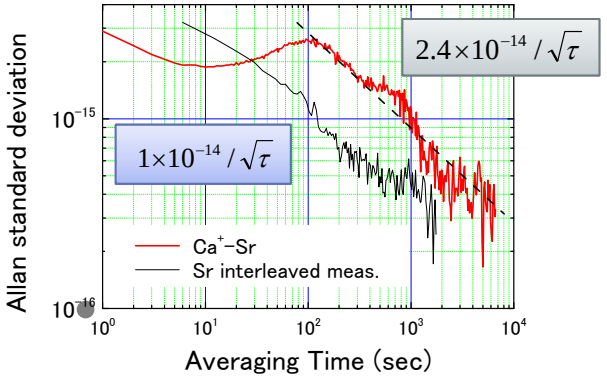
Direct comparison

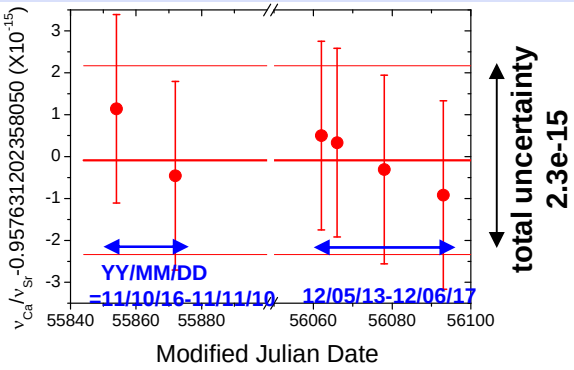


Absolute frequency measured at NICT



Frequency comparison between Ca^{+} ion clock and Sr lattice clock





- ν_{Ca}/ν_{Sr} = 0.957 631 202 358 049 9 (2 3)
- Fractional uncertainty 2.3e-15
- Evaluation Ca^{+} ion clock using Sr lattice clock as a reference

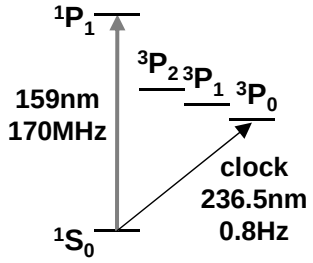
$^{115}In^+$ single-ion optical clock

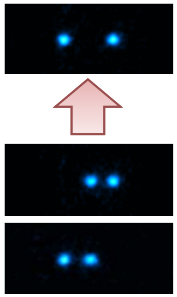
Target:

- Accuracy in the order of 10^{-18}

New approaches:

- Sympathetic cooling with Ca^+
- Fast state detection
  - Simplified quantum logic
  - Direct excitation of VUV transition (159nm)
- Hybrid clock with the Sr optical lattice clock





(Ca^+,In^+,Ca^+)

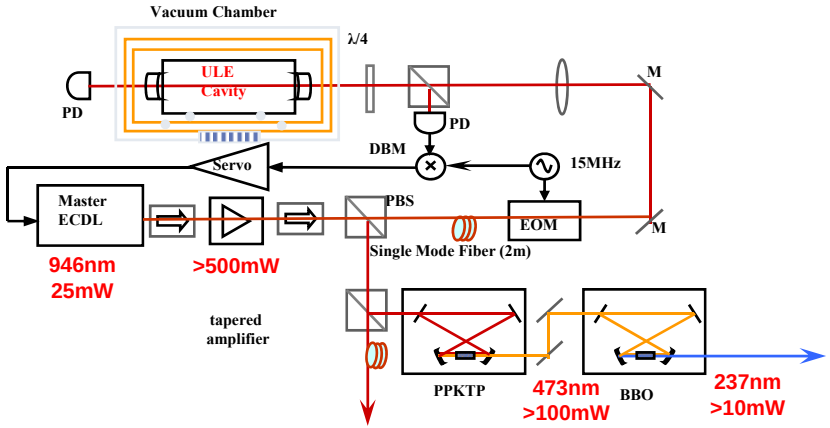
aligning laser pulse

(In^+,Ca^+,Ca^+)

(Ca^+,Ca^+,In^+)

Method for preparing the In^+-Ca^+ ion chain in a linear trap has been established (Appl. Phys. B, 107,965(2012)

- The clock laser system with Hz-order linewidth is ready



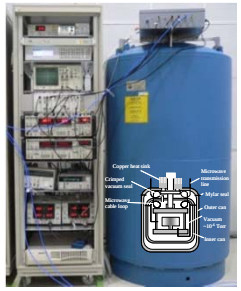
- The first clock operation is planned in FY2013 with an initial accuracy of 10^{-14}

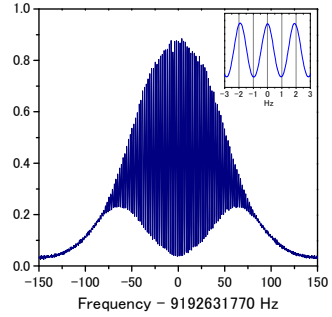
Cs fountains as PFS

NICT-CsF1

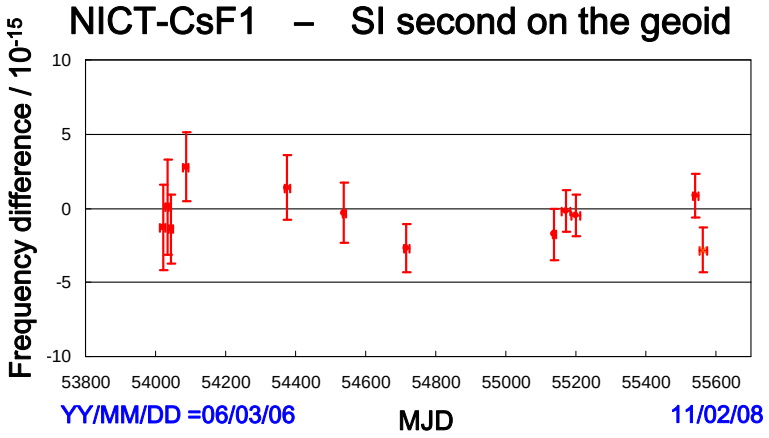
NICT-CsF2

CSO (Cryogenic Sapphire Oscillator)

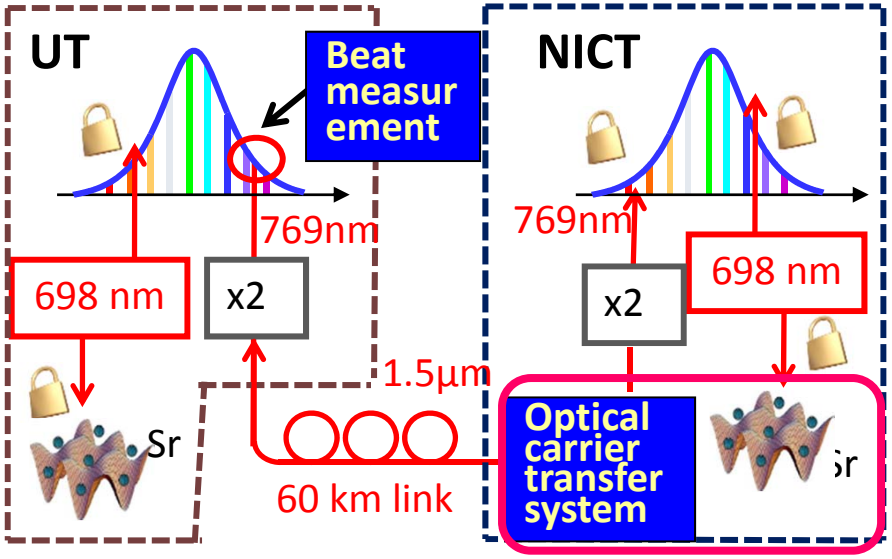




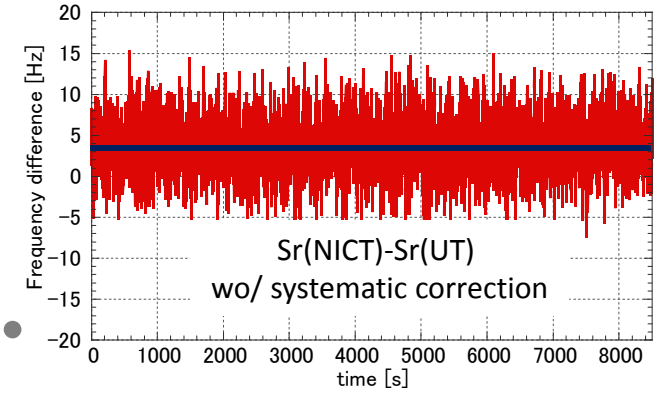
- 12 accuracy evaluation campaigns have been reported to BIPM since 2006.
- Cs-F2 based on optical molasses is under development.



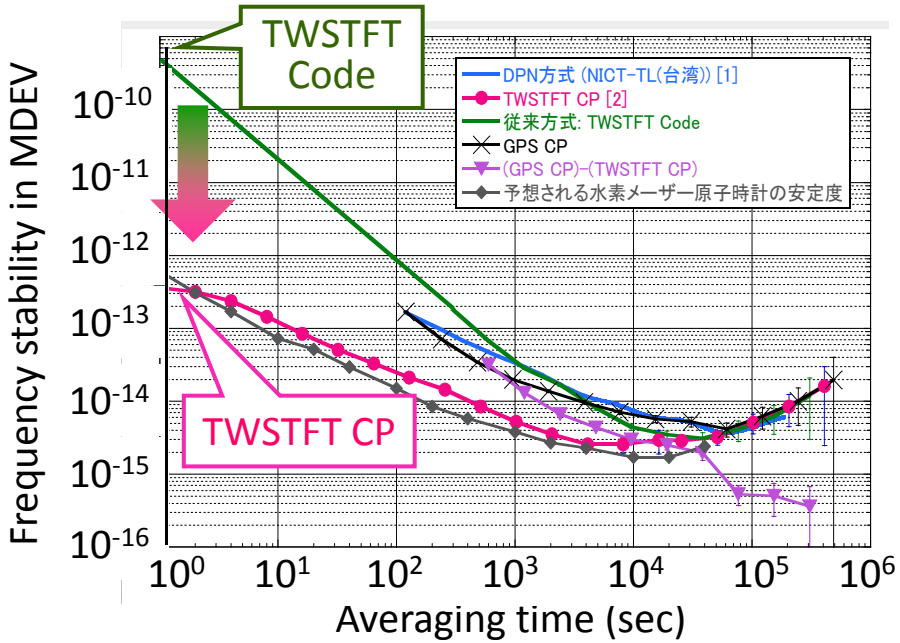
Optical fiber link between NICT and UT



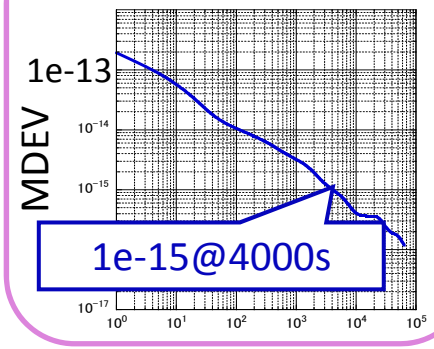
* All optical link system achieved 2e-15 @ 1 s and 7e-17 @ 1000 s.
* 2 remote Sr lattice clocks agreed in 10^{-16} level.
* Frequency shift of 2.6 Hz attributed in elevation difference of 56 m was detected after 10 s average.



Carrier phase TWSTFT

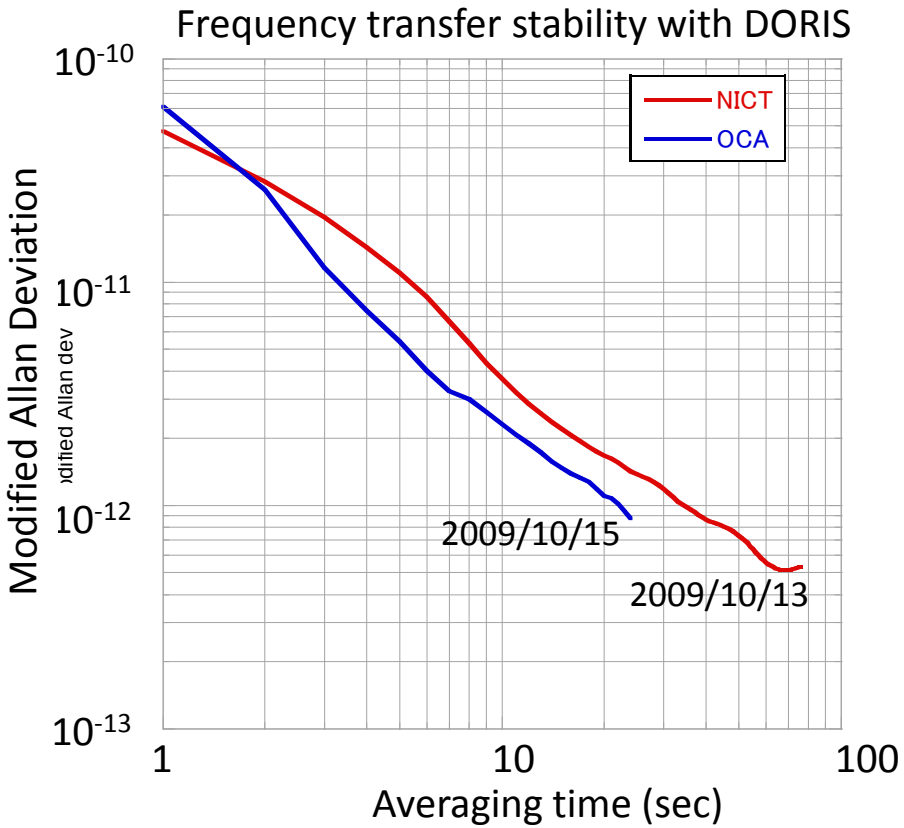


* Operational carrier phase TWSTFT via a geostationary satellite was demonstrated in 150-km baseline for the first time.
* Measurement precision of 0.4 ps was achieved. (1000 times better than conventional TWSTFT.)
* Common-clock measurem
  2e-13@1s
  1e-15@4000s
  are achieved.
* This is comparable to inter-continental ACES MWL.

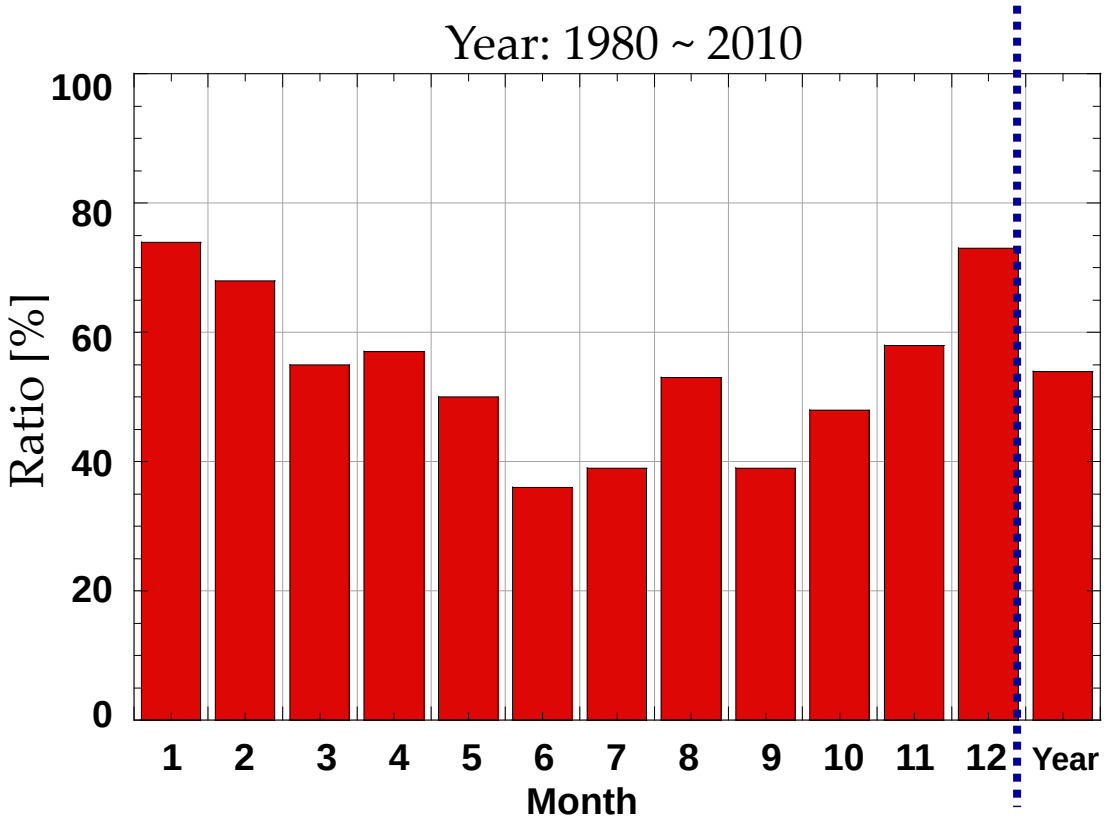


SLR station in NICT

- Koganei (7308): Optical Communication Ground Station since 1990.
  - ✓ Telescope Aperture: 1.5 m
  - ✓ Laser :532 nm 50 mJ 20 Hz, 50ps pulse width
  - ✓ UTC(NICT) signal has been provided through optical fibers since 2009.
- Koganei (7308) joined the T2L2 campaign in October 2009.
- The laser will be renewed in 2014.
- Operation continuity of the telescope is under discussion.



Weather condition in Tokyo



Month	Ratio [%]
1	74
2	68
3	55
4	57
5	50
6	36
7	39
8	53
9	39
10	48
11	58
12	73
Year	54

- Ratio of number of days for actual sunshine duration > 40 %.
- Reference: Japan Meteorological Agency,

http://www.data.jma.go.jp/obd/stats/etrn/view/nml_sfc_ym.php?prec_no=44&block_no=47662&year=&month=&day=&view=a4

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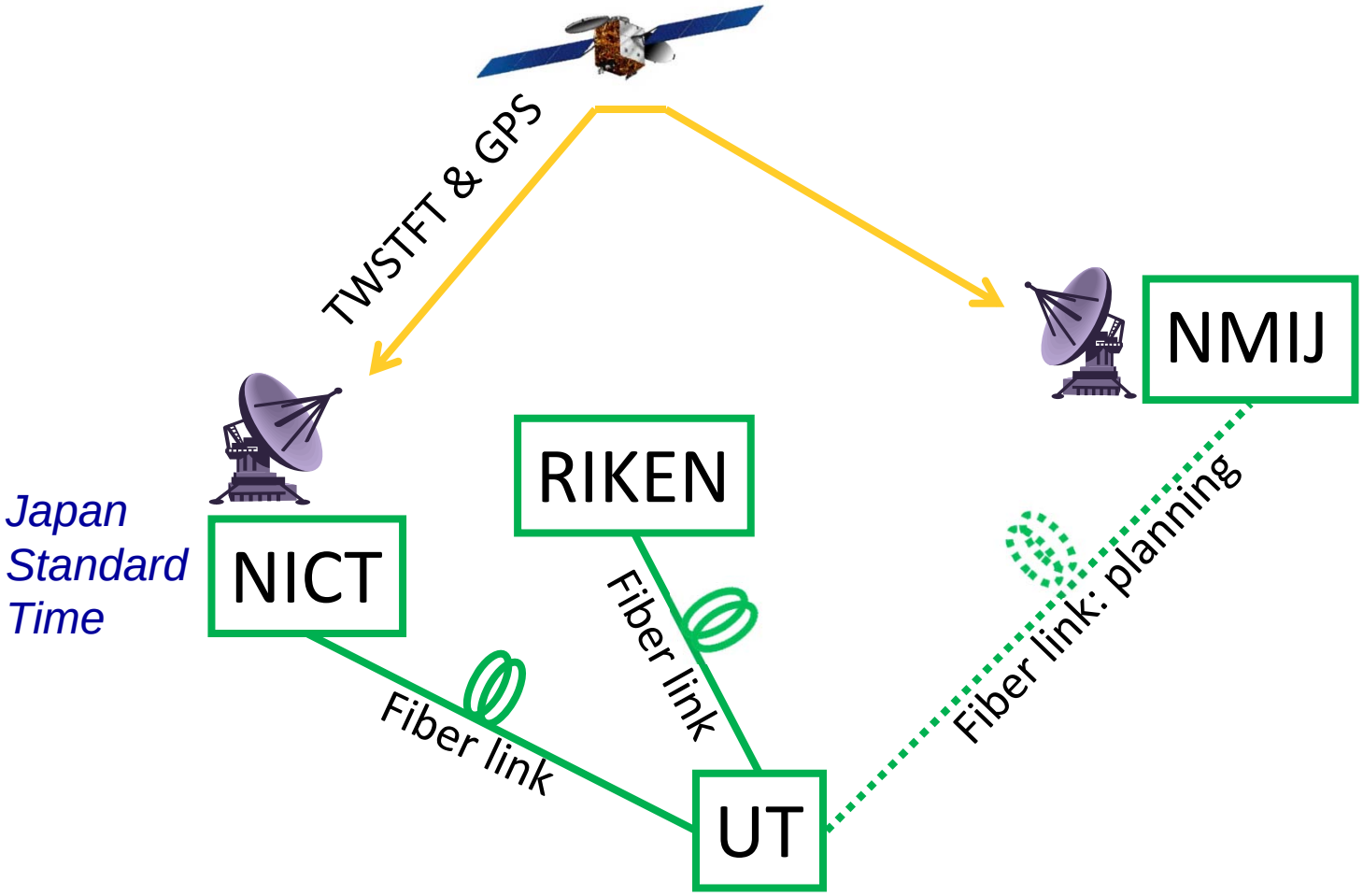
Summary of atomic clocks

Site	Atomic clocks including under development
NMIJ	Yb lattice clock Sr-Yb lattice clock NMIJ-F1 NMIJ-F2
NICT	^{87}Sr lattice clock Ca+ single ion clock In+ single ion clock NICT-CsF1 NICT-CsF2
UT & RIKEN	3 ^{87}Sr lattice clocks (1 in UT, 2 in RIKEN) 2 Hg lattice clocks (2 in RIKEN)
Total	**4 Cs fountains** **2 single ion clocks** **8 optical lattice clocks**

Summary of frequency links



4 institutes can be linked by fiber links or satellite links.

Summary

- **Various optical clocks are being developed at 4 institutes (NMIJ, NICT, Univ. Tokyo and Riken) around Tokyo area.**

- **These institutes can be linked by optical fiber or satellites, and collaborate together to join ACES (If its ground terminal comes to Japan).**