Developments of Optical Clocks and their Comparisons for Future Time Reference

Yasuhiro Koyama, Miho Fujieda, Hidekazu Hachisu, Tetsuya Ido, Reiko Kojima#, Motohiro Kumagai, Ying Li, Kensuke Matsubara, Shigeo Nagano, Nobuyasu Shiga, Atsushi Yamaguchi*, Tadahiro Goto, Yuko Hanado, and Mizuhiko Hosokawa

National Institute of Information and Communications Technology (NICT) Japan

(# retired, * currently at PTB, Germany)

Contents

Background and Purpose of the Work

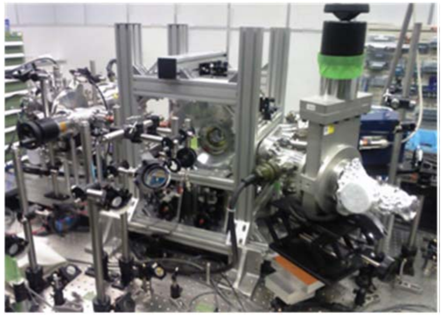
Optical Frequency Standards at NICT

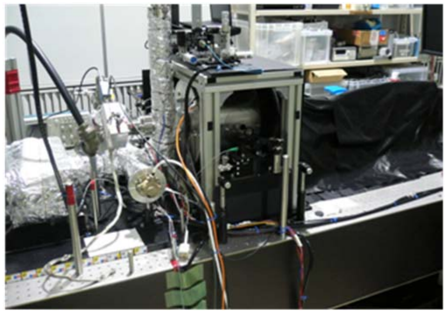
- ^{87}Sr Lattice clock
- $^{40}Ca^+$ Single Ion Trap

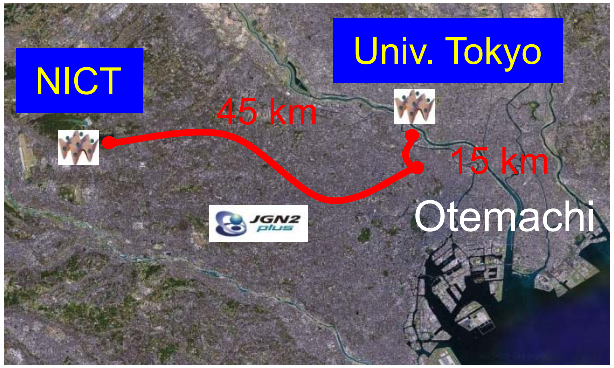
^{87}Sr Comparison by Optical Fiber Link between NICT and Univ. Tokyo

$^{40}Ca^+$ Comparison by GPS between NICT and WIPM (Wuhan, China)

Conclusions and Future Plan


^{87}Sr Lattice Clock


$^{40}Ca^+$ Single Ion Trap



Optical Fiber Link

Optical Frequency Standards: 10^{-16} level comparison is desired

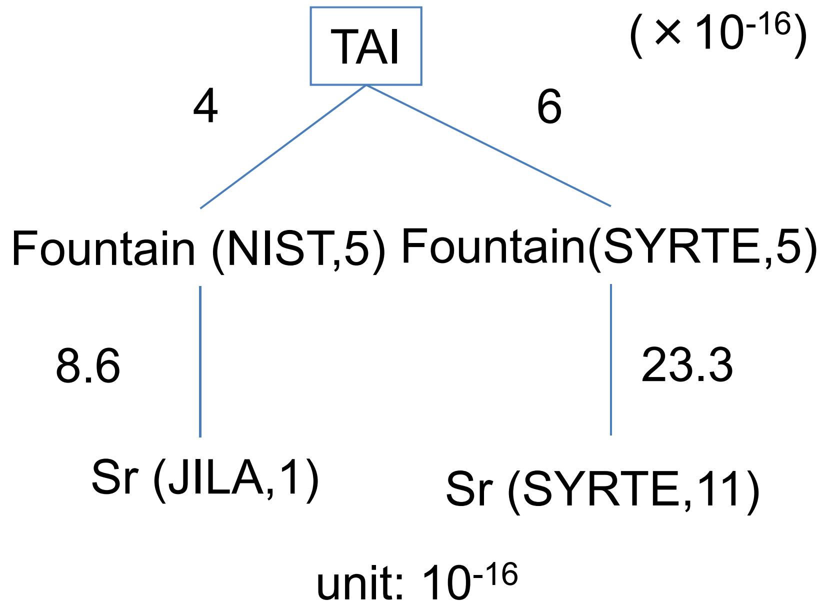
Second representation of the second by ^{87}Sr

429 228 002 229 873. 65 Hz uncertainty: 1×10^{-15}

10^{-16} level of uncertainties have been reported from three labs.
However,… Do they REALLY generate same frequency?

$\times 10^{-16}$

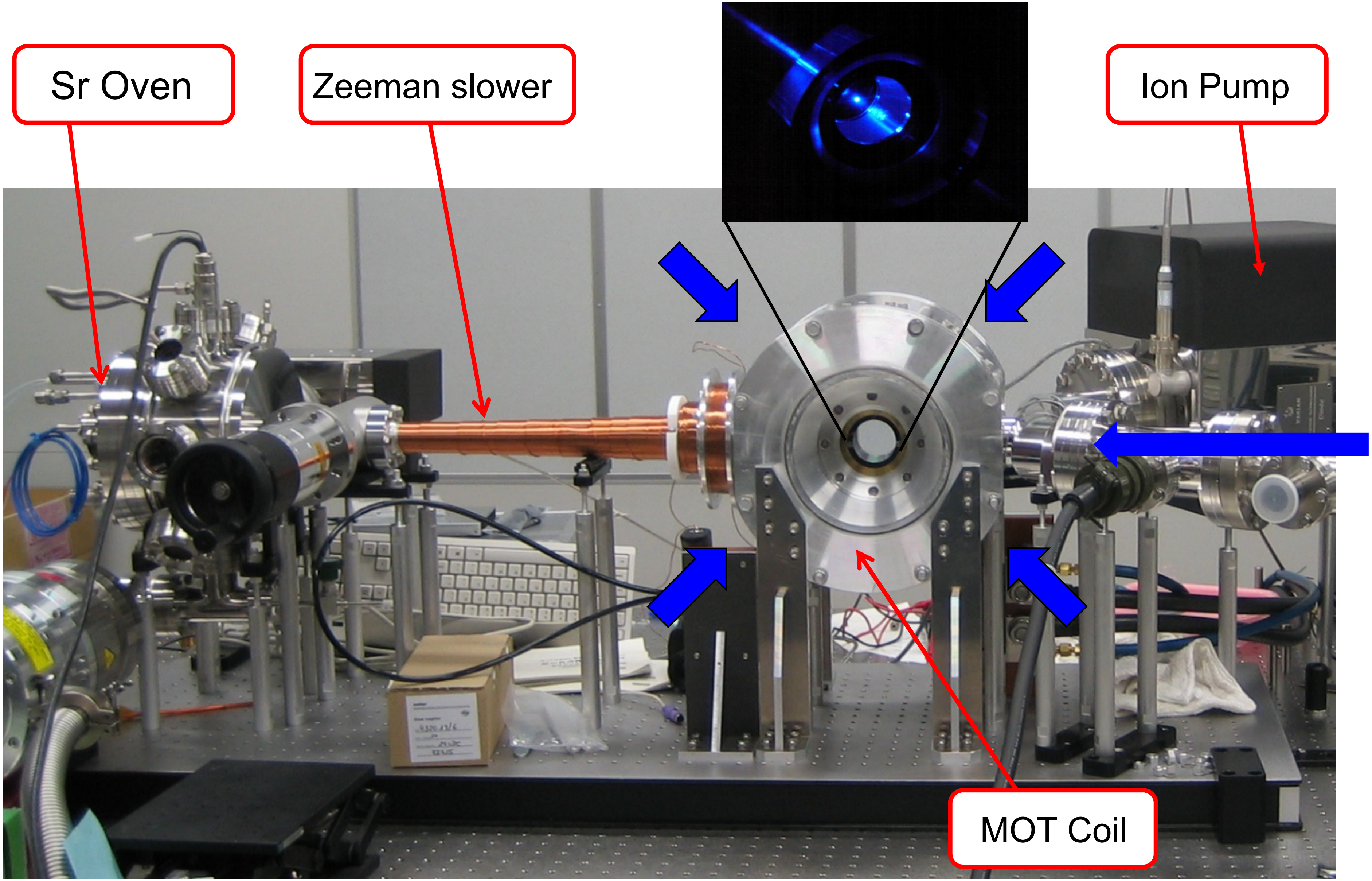
	JILA [2]	SYRTE [3]	UT -NMIJ [1]
Sr	1.4	11.2	5.8
Sr-Fountain	8.6	23.3	52
Fountain	5	5	
Fountain-TAI	4	6	16



Goal
Confirmation of frequency agreement in ~10^{-16} between the optical frequency standards

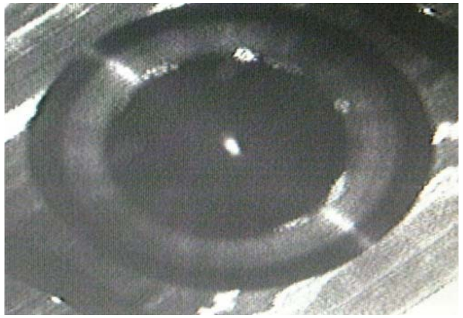
[1] Opt. Lett. 34 692 (2009).
[2] Metrologia 45 539 (2008).
[3] EPJD 48 11 (2008)

^{87}Sr lattice clock at NICT



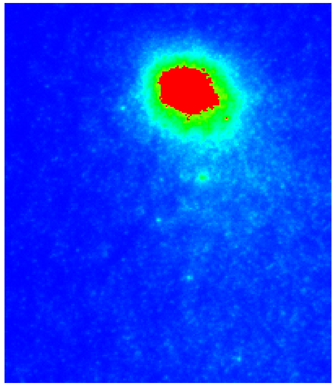
High resolution spectroscopy of ^{87}Sr clock transition

Blue MOT
(1st cooling)



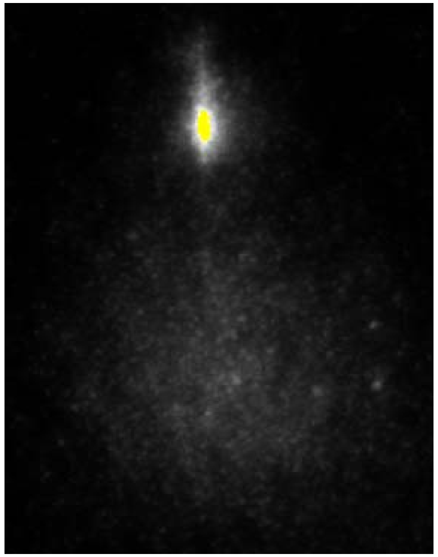
N **~ 3 x 10^5**
T **~ 2 mK**

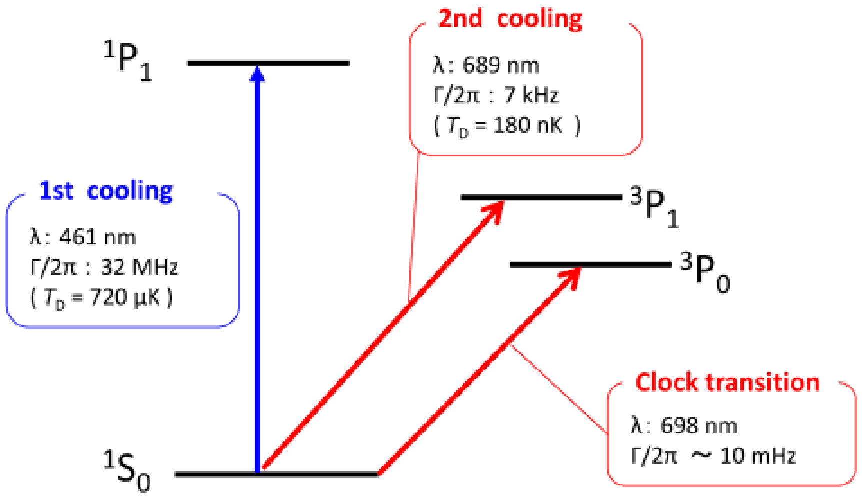
Red MOT
(2nd cooling)

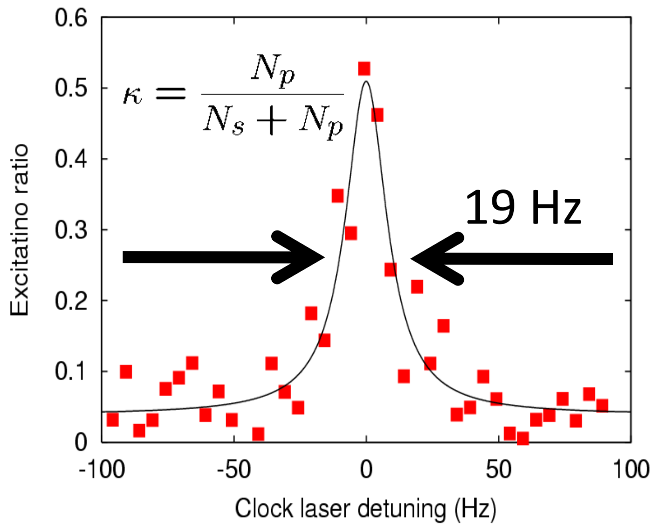


N **~ 5 x 10^4**
T **~ 3 μK**

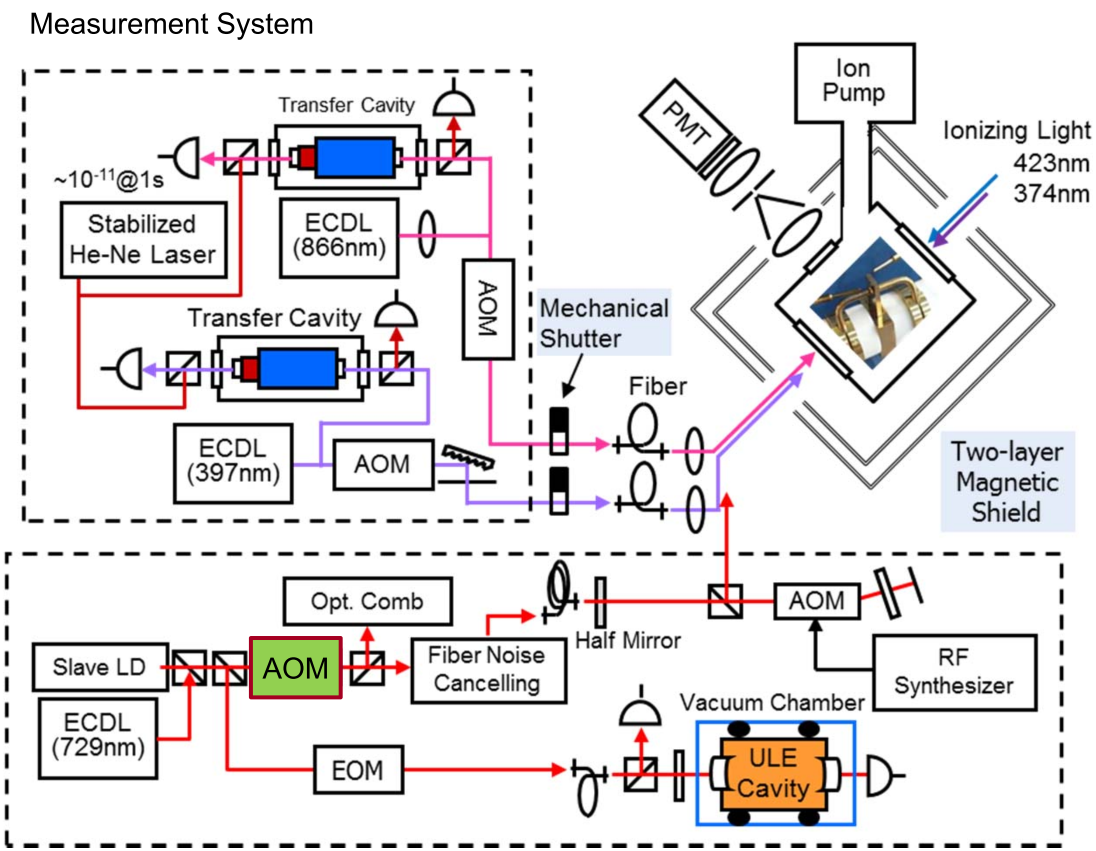
1D Lattice

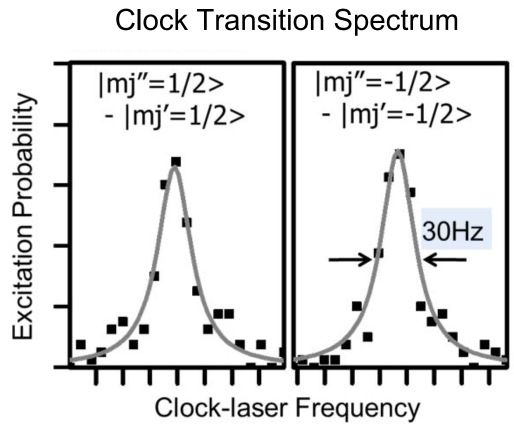


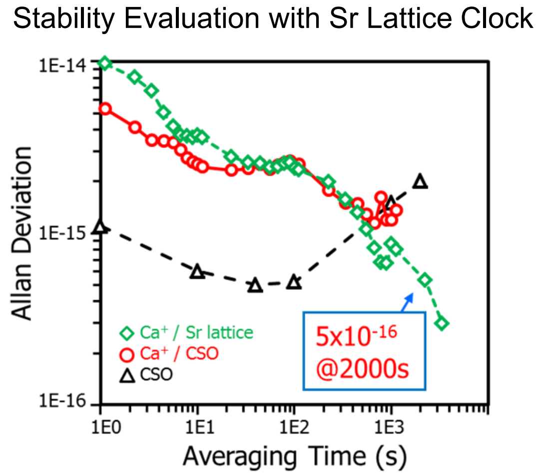




$^{40}Ca^{+}$ Single Ion Trap Optical Frequency Standard

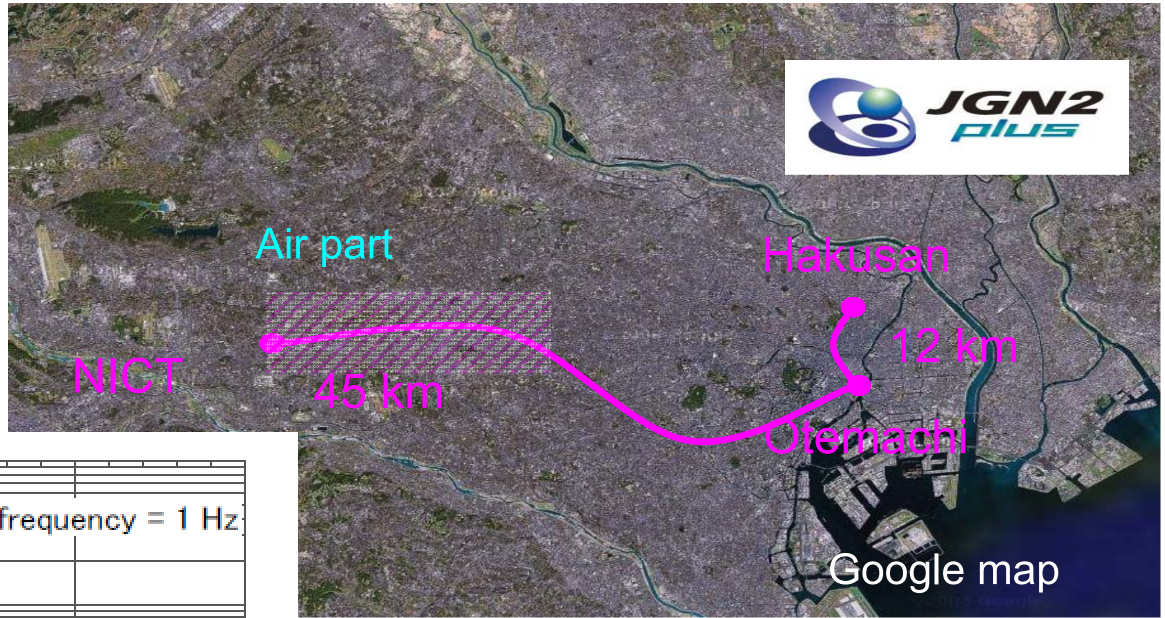




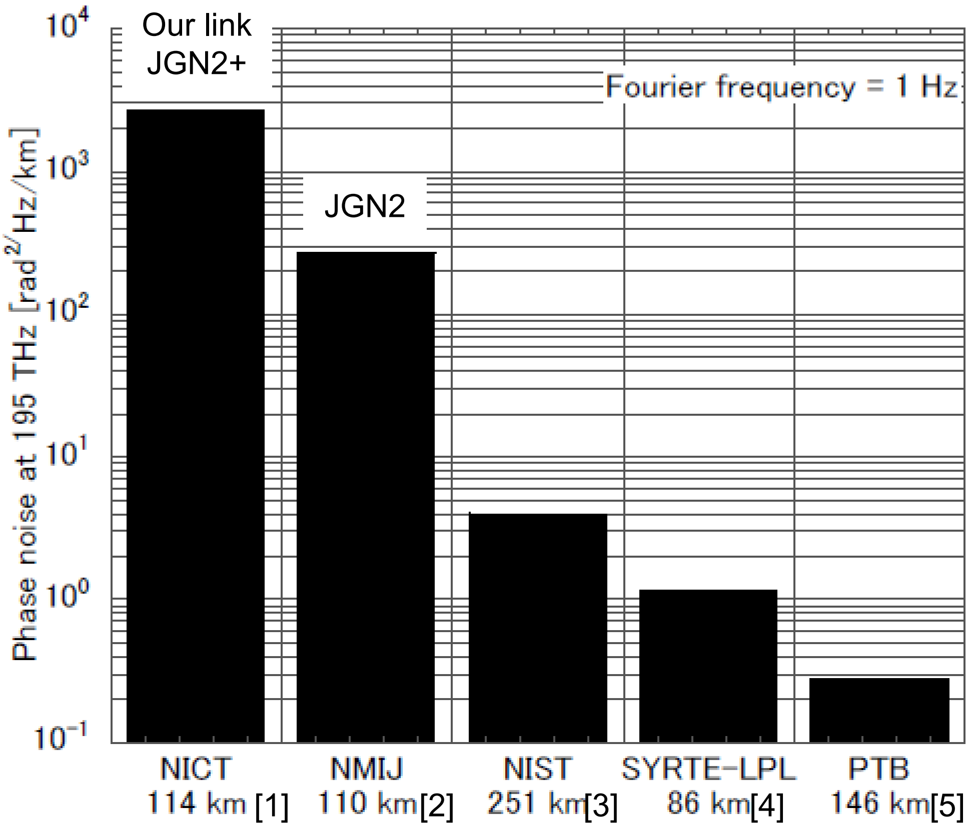


Measured Frequency : 411 042 129 776 398.4 (1.2) Hz

Fiber Link Comparison between NICT-Univ.Tokyo



Phase noise per 1km



[1] M. Kumagai et al.,
Opt. Let., 34, 19, 2949-2951, 2009.

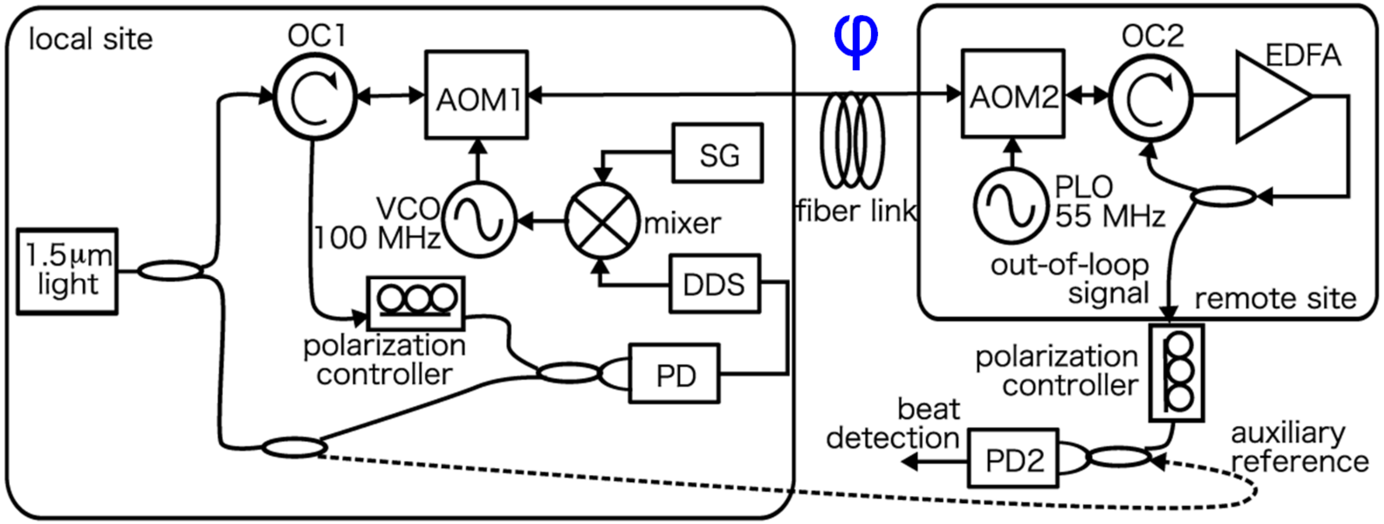
[2] M. Musha et al.,
Opt. Exp., 16, 21, 16459-16466, 2008.

[3] N. Newbury et al.,
Opt. Let., 32, 21, 3056-3058, 2007.

[4] H. Jiang et al.,
J. Opt. Soc. Am. B, 25,12,2029-2035,2008.

[5] G. Grosche et al.,
arXiv:0904.2679v1, 2009.

Optical Fiber Transfer System



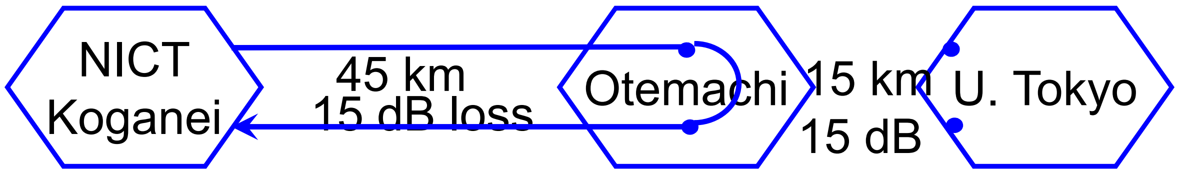
- Double fiber noises, 2φ, canceled at the local site

  ➡ φ＝0 at the remote site

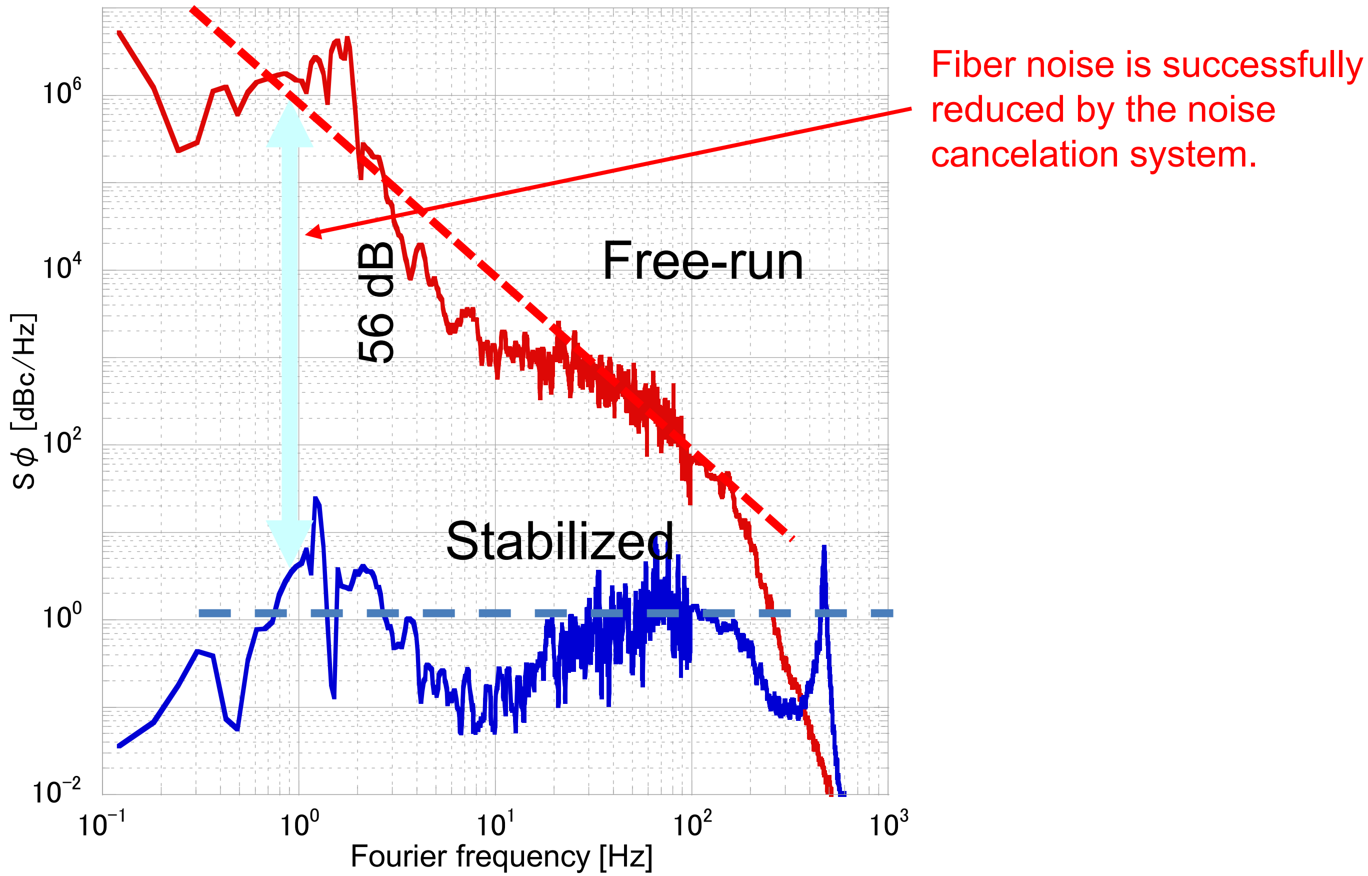
- Optical source: fiber laser locked to ULE cavity

  Stability ~ 2×10^{-14} @ 1 s, Line width < 10 Hz

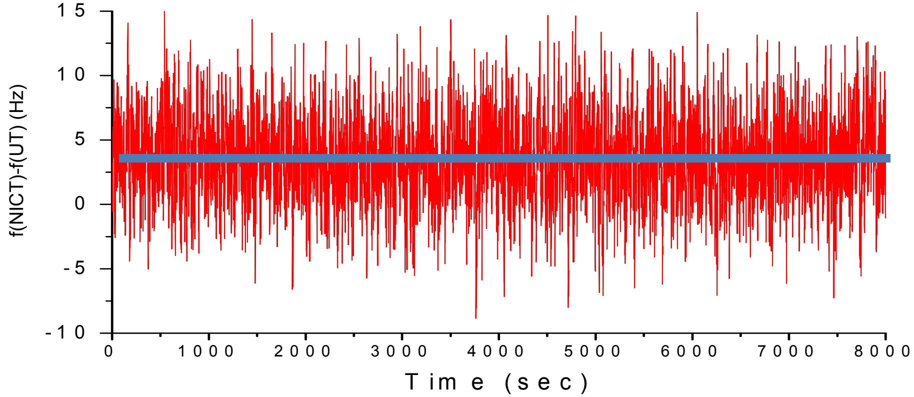
Evaluation of the stabilized fiber link



Total length: 90 km, optical loss: 30 dB



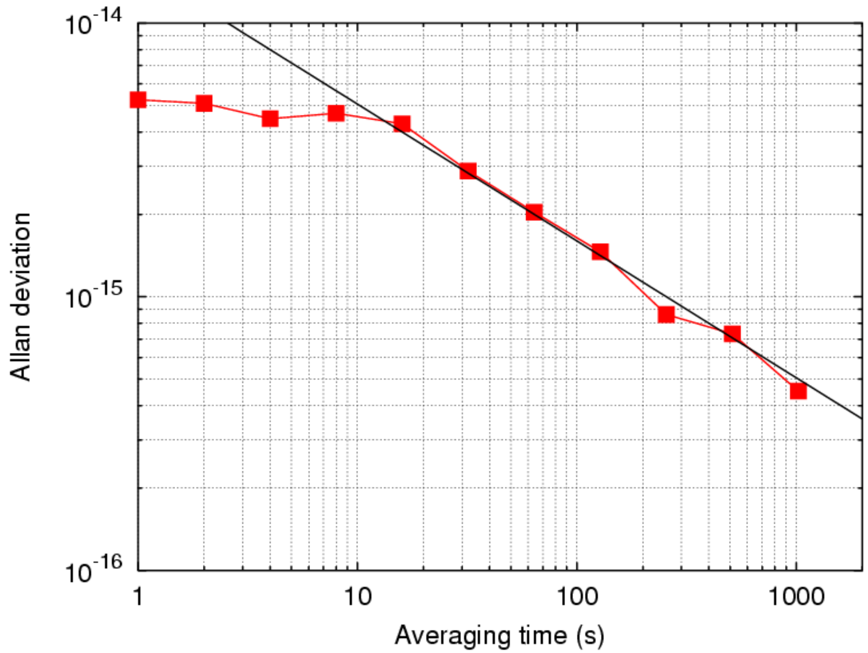
Difference & instability obtained by the fiber link



Offset
predominantly due to differential gravity shift

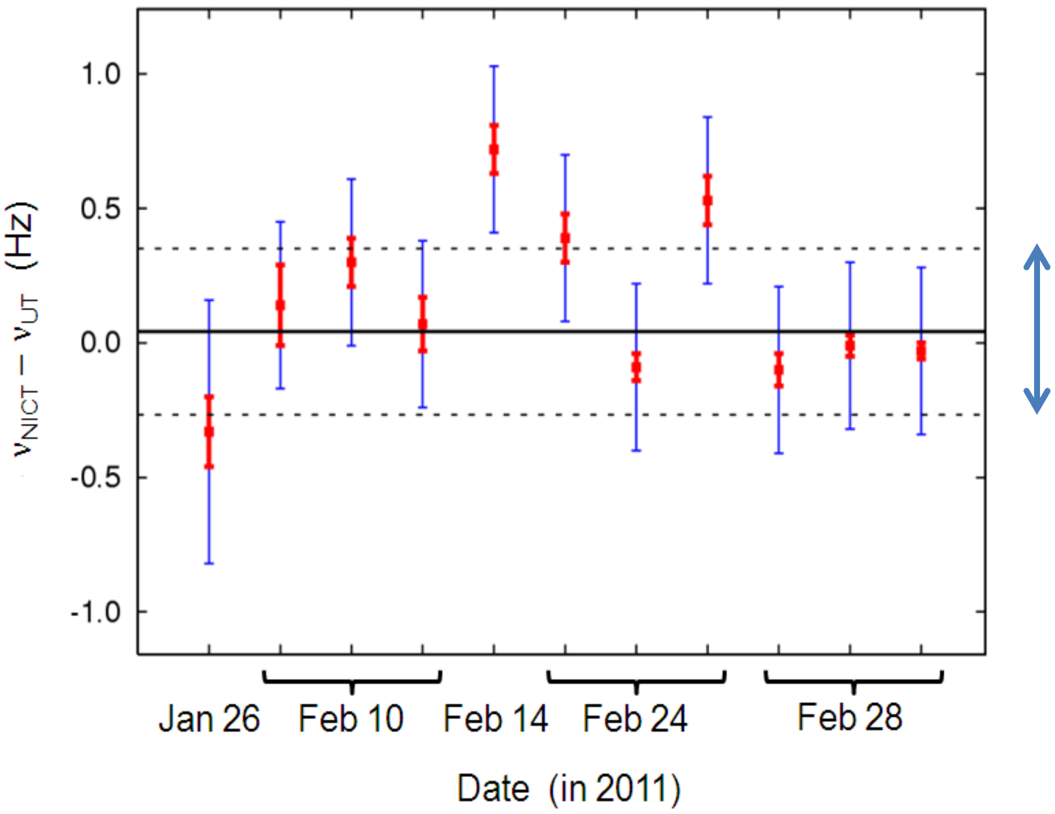
55m elevation difference
→ 2.6Hz higher frequency in NICT

$$\Delta\nu = \frac{mg\,\Delta h}{mc^2}\nu = \frac{9.8[\mathrm{m/s^2}]\times 56[m]}{\left(3\times 10^8[m/s]\right)^2}\times 429\mathrm{THz} = 2.6Hz$$



The instability of lately developed NICT Sr clock was REMOTELY characterized by the comparison against UT clock.

Difference of intrinsic resonances



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

Total systematic uncertainty of two clocks (0.36Hz)

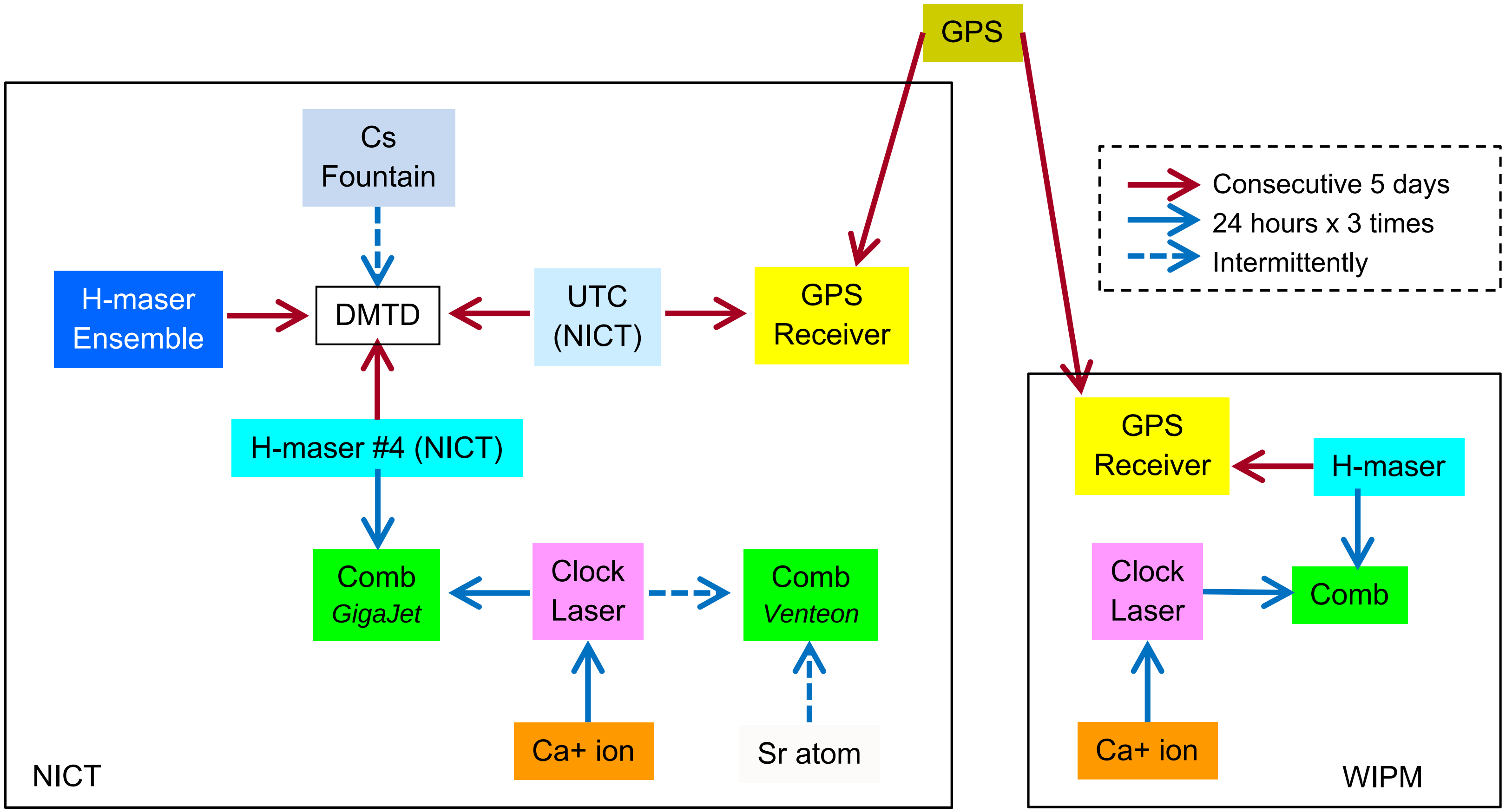
No limitation by the fiber transfer

Weighted average 0.04Hz (1.0×10^{-16}) < Total Systematic uncertainty 0.36Hz (8.4×10^{-16})

→ systematic shifts are well managed & evaluated. No critical unknown shift

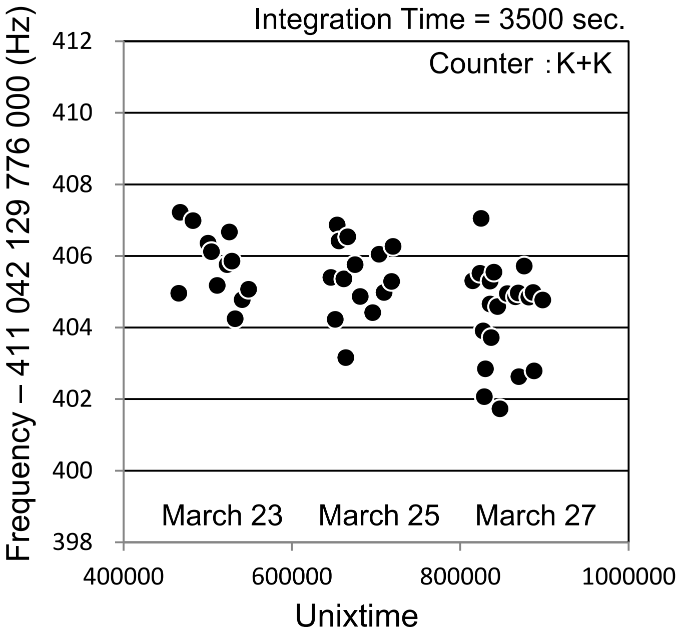
GPS frequency comparison between NICT-WIPM

GPS Data Period : March 23–27, 2012 (MJD 56009 - 56013)
Clock Comparisons on March 23, 25, and 27 (24 hours from 0:00 (UTC))



GPS frequency comparison between NICT-WIPM

Measured frequency of Ca^+ transition
at NICT referred to a H-maser.



Evaluation of Ca^+ Transition Frequency by using 3 counters
(only the frequency part below 1000Hz is shown)

		K+K	Pendulum 1	Pendulum 2	Average
March 23	Frequency (Hz)	405.8	404.8	405.0	405.2 (0.8)
	Integration (sec)	45653	50021	50019	
March 25	Frequency (Hz)	405.4	405.4	405.4	405.4 (0.8)
	Integration (sec)	67911	60476	60477	
March 27	Frequency (Hz)	404.9	405.0	404.7	404.9 (0.8)
	Integration (sec)	65330	58316	58301	

Frequency comparison between NICT and WIPM (Unit : Hz)

	NICT (H-maser reference)		WIPM (H-maser reference)		Frequency difference referenced to each H-maser	Frequency difference of H-masers	Residual
	Systematic Shift	After Correction *	Systematic Shift	After Correction *			
March 23	4.1 (0.9)	401.1 (1.2)	1.7 (0.5)	526.6 (5.6)	125.5	129.1 (1.0)	3.6 (5.7)
March 27	4.1 (0.9)	400.8 (1.2)	1.7 (0.5)	526.5 (5.1)	125.7	129.7 (1.0)	4.0 (5.2)

* only the frequency part below 1000Hz is shown

→ frequency comparison at the level of 2.5 x 10^{-15} with 1 day has been succeeded

Conclusions and Future Plan

Direct optical comparison of ^{87}Sr Lattice Clocks at NICT and Univ. Tokyo yielded a good agreement with the uncertainty of 8 x 10^{-16}.

GPS comparison of $^{40}Ca^{+}$ Single Ion Trap systems at NICT and WIPM was successfully demonstrated with the uncertainty of 2.5 x 10^{-15} with 1 day.

Efforts to improve the current comparison methods as well as the developments of new methods (such as a carrier phase method using Two Way Satellite Time and Frequency Transfer, and a method using Very Long Baseline Interferometry (Poster by M. Sekido)) are desired for much precise comparisons of optical frequency standards.

Acknowledgements

The authors would like to express special thanks to Prof. Katori and his group at Univ. of Tokyo, and Prof. Gao and his group at Wuhan Institute of Physics and Mathematics for their collaboration to conduct comparison experiments.

Thank you very much for your kind attention.