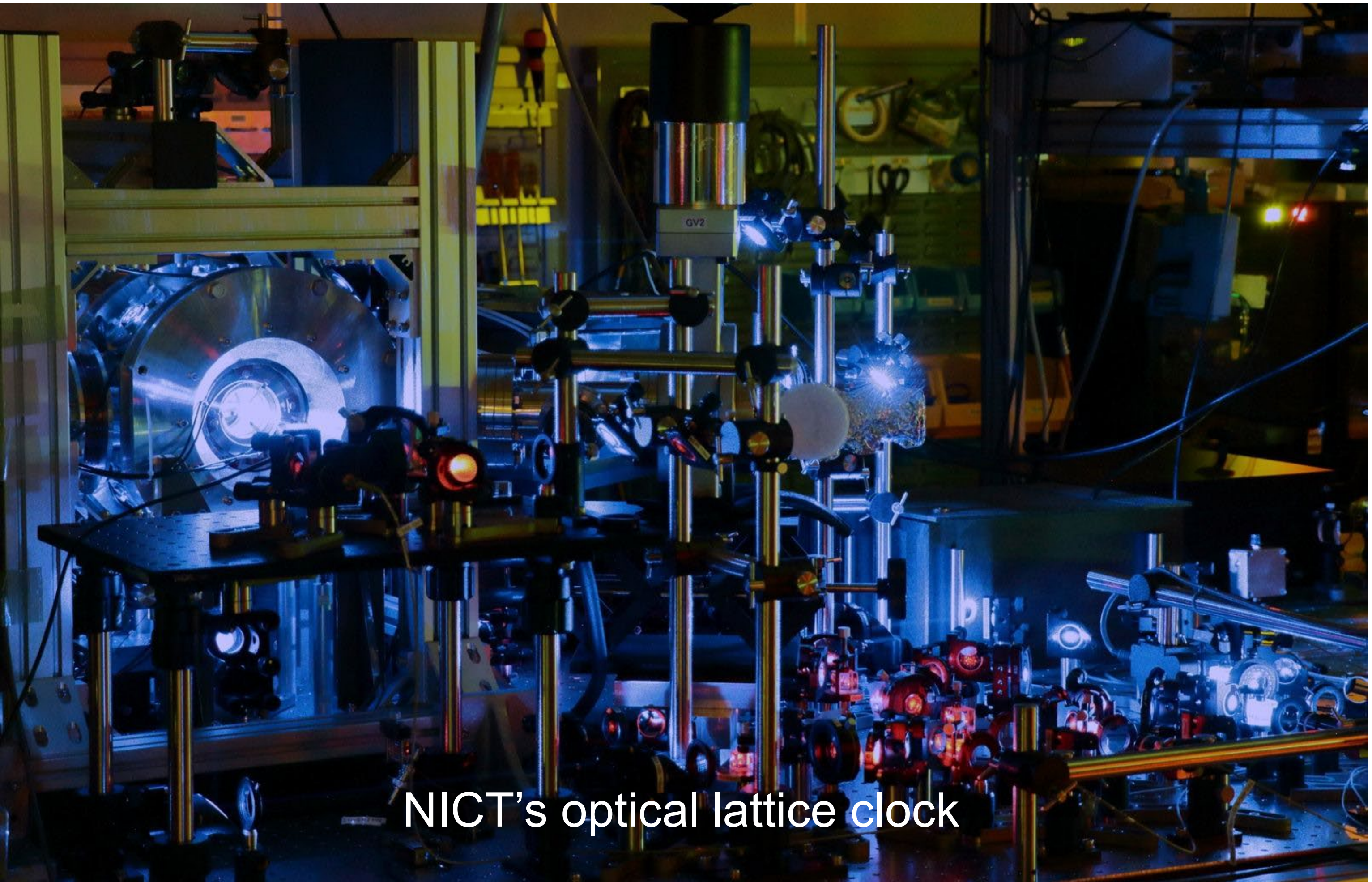
Generating and Monitoring UTC(NICT) with an Optical Lattice Clock



NICT's optical lattice clock

BIPM UTC Summer School
2025/09/11
BIPM

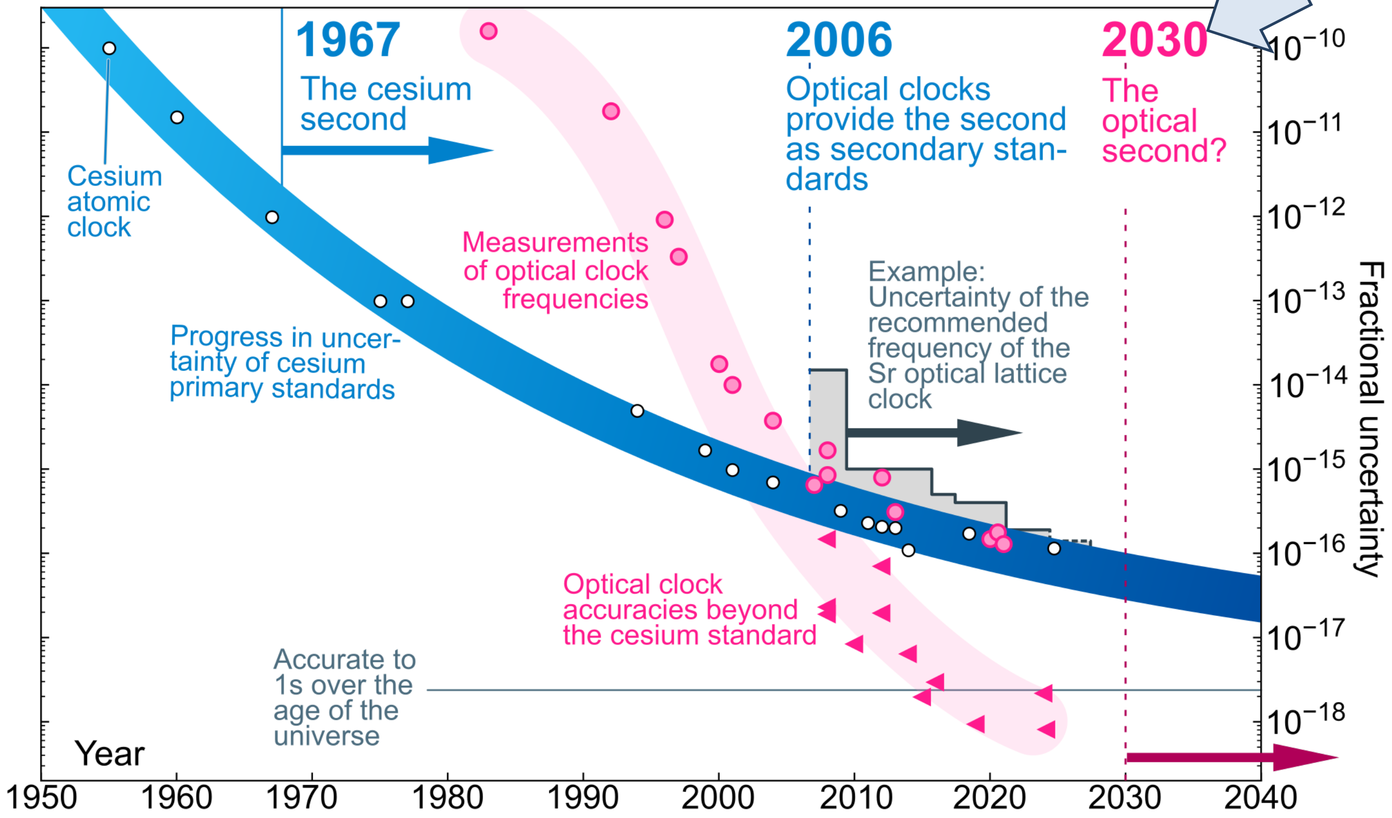
Hidekazu Hachisu

NICT

NICT National Institute of Information and Communications Technology

Questions welcome during the coffee break or by email after the talk

Redefining the SI Second



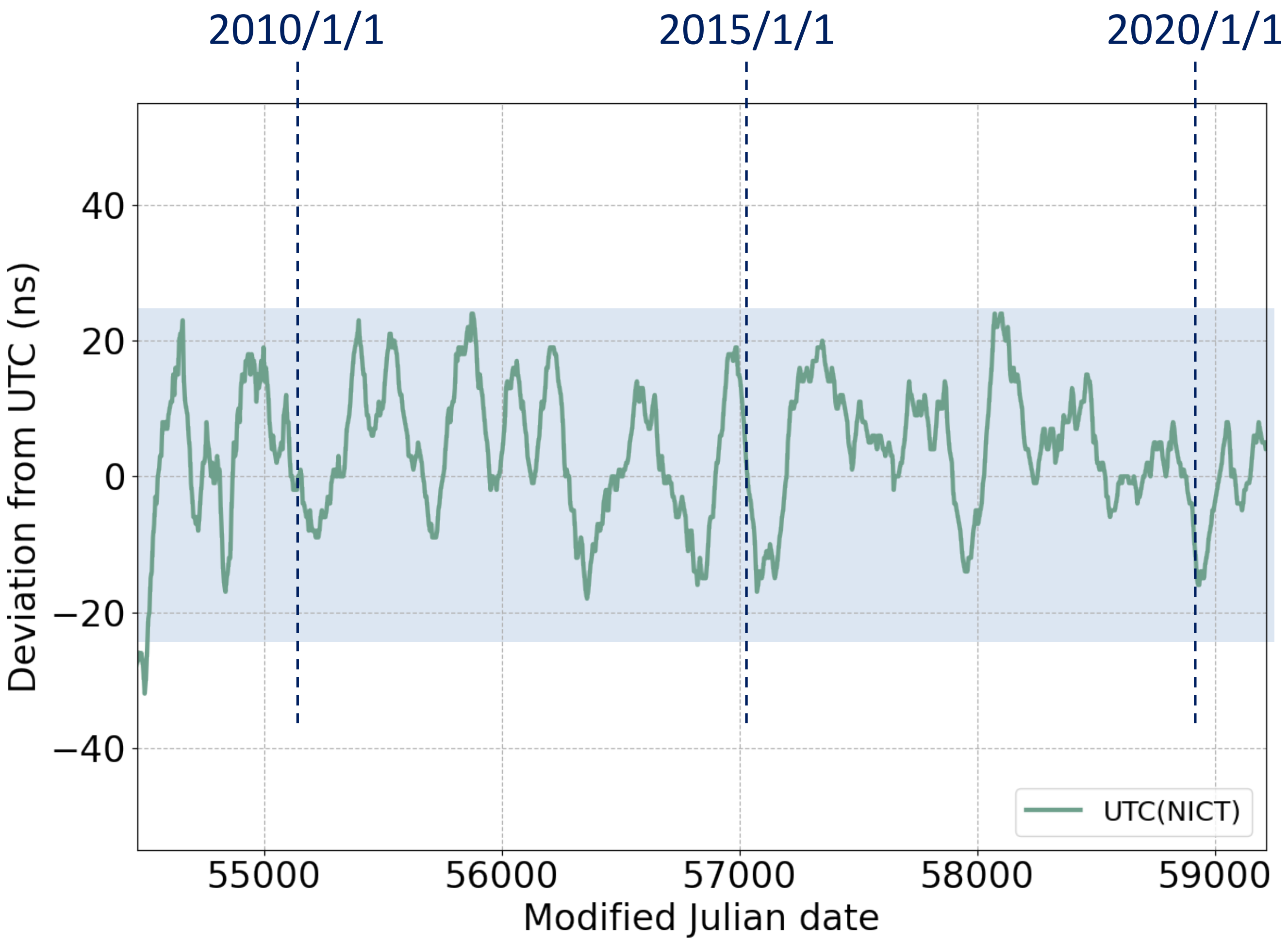
Adapted from H. Margolis, IEEE IFCS-UFFC Join Symposium 2024

The International Committee for Weights and measures (CIPM) is currently considering a redefinition of the SI second, possibly as early as 2030.

- *F. Riehle, "Towards a redefinition of the second based on optical atomic clocks", C. R. Physique **16**, 506–515 (2015).*
- *F. Riehle, P. Gill, F. Arias, L. Robertsson, "The CIPM list of recommended frequency standard values: guidelines and procedures", Metrologia **55**, 188-200 (2018).*
- *N. Dimarcq et al., "Roadmap towards the redefinition of the Second","Metrologia **61**, 012001 (2024).*

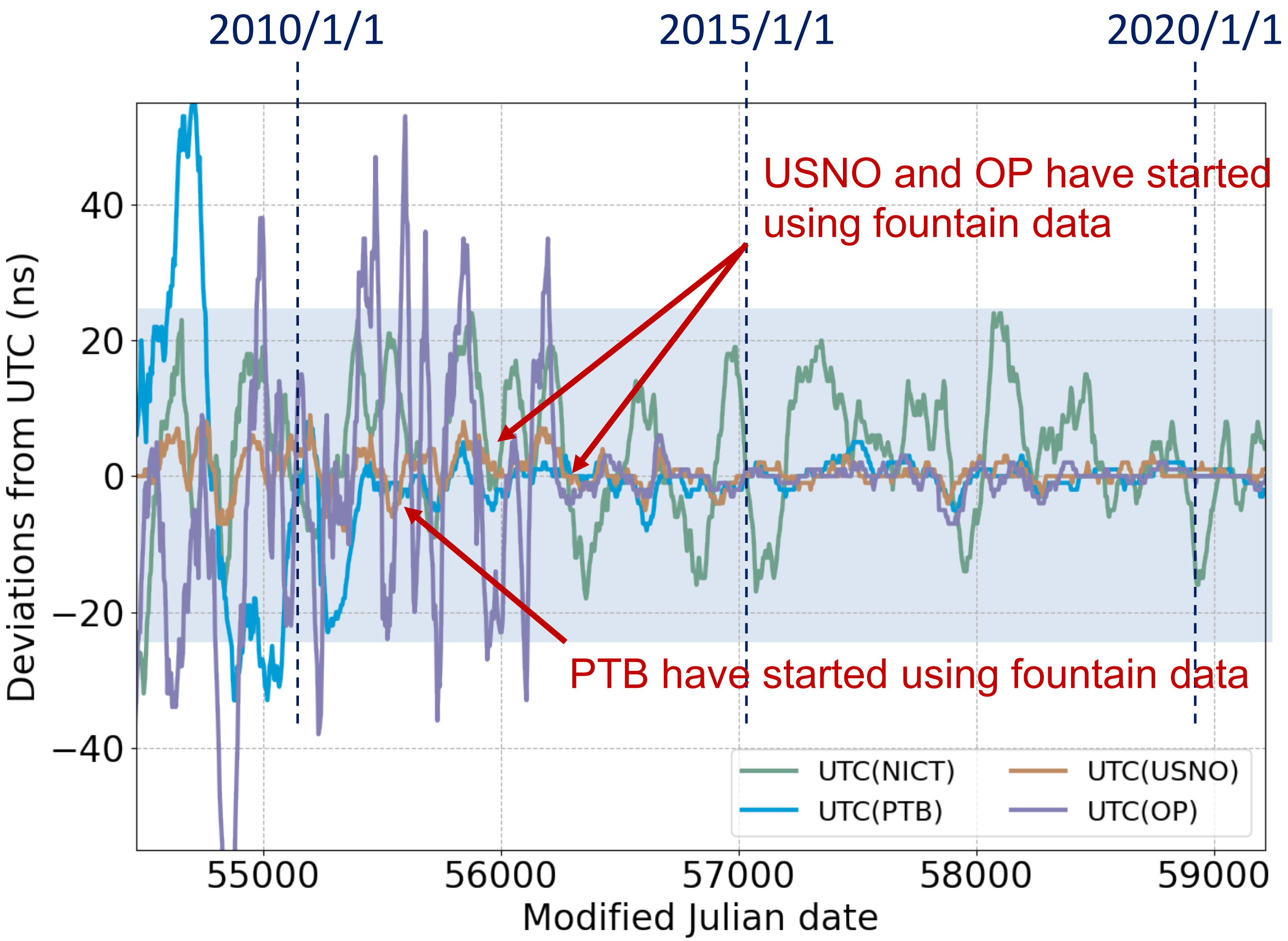
The Consultative Committee for Time and Frequency (CCTF) has identified contributions from optical clocks to timescales as one of the key criteria for redefining the SI second—from the current microwave transition in cesium to one or more optical transitions.

Deviations of UTC(*k*) from UTC



UTC(NICT) has consistently tracked UTC with a deviation of no more than ±25 ns over the past ten years.

Deviations of UTC(*k*) from UTC



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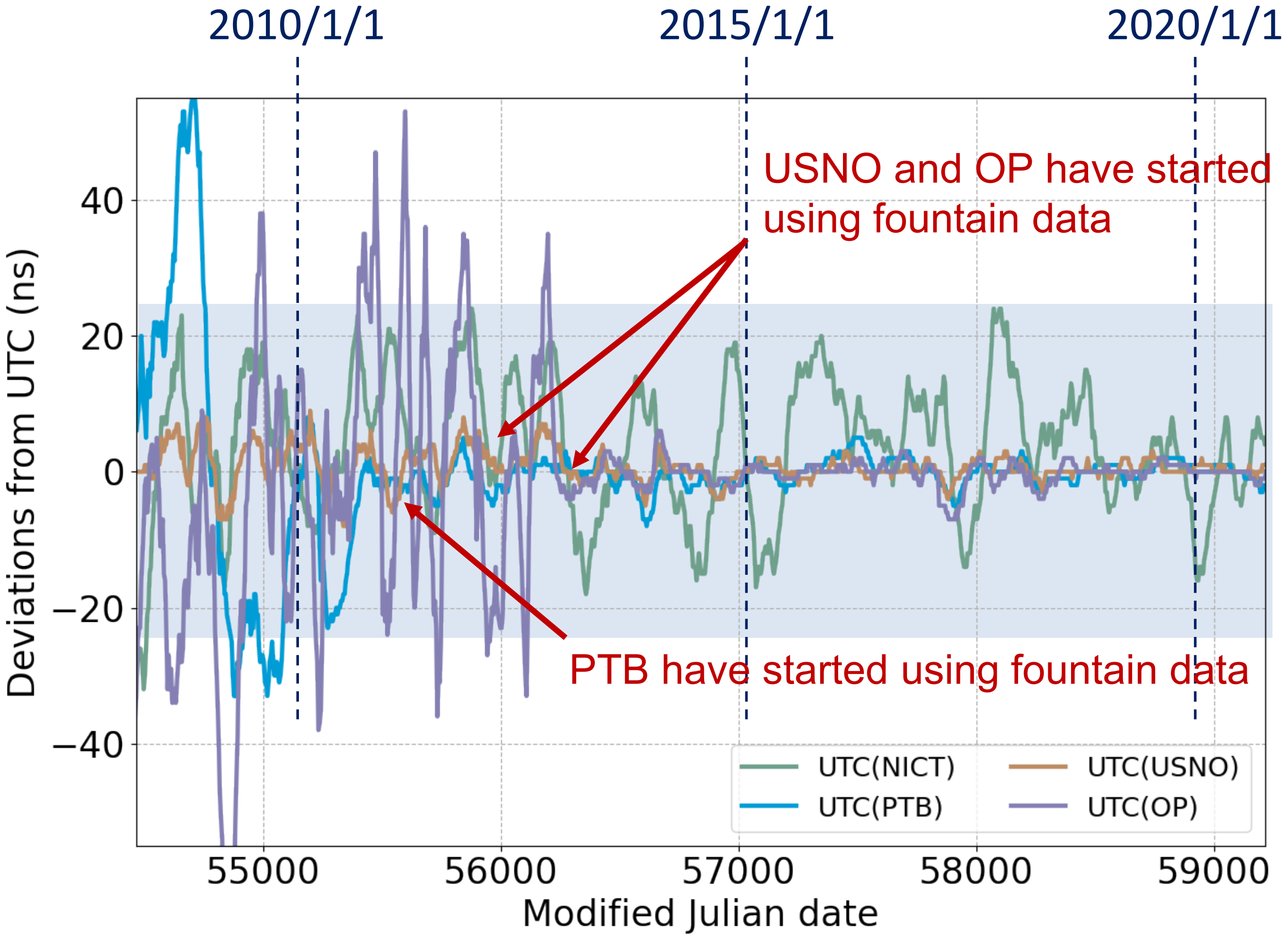
PTB, USNO, and OP have introduced UTC(*k*) steering based on continuously operating **cesium or rubidium fountain clocks**.

- *A. Bauch et al., "Generation of UTC(PTB) as a fountain-clock based time scale", Metrologia* ***49****, 180 (2012).*
- *S. Peil et al., "Evaluation of long term performance of continuously running atomic fountains", Metrologia* ***51****, 263 (2014).*
- *G. D. Rovera et al., "UTC(OP) based on LNE-SYRTE atomic fountain primary frequency standards", Metrologia* ***53****, S81 (2016).*

Deviations of UTC(*k*) from UTC



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NICT is aiming to steer UTC(NICT) using its optical clock.

- *T. Ido et al., "Rapid evaluation of time scale using an optical clock", Proceedings for the 8th Symposium on Frequency Standard and Metrology [J. Phys. Conf.* ***723****, 012041 (2016)].*

Ongoing Work on Optically Steered Timescales

- ✓ **Recently, some institutes have begun applying optical clocks to a timescale generation through post-processing of measurement data.**
  - ☐ *T. Ido et al., "Rapid evaluation of time scale using an optical clock", Proceedings for the 8th FSM [J. Phys. Conf.* ***723****, 012041 (2016)].*
  - ☐ *C. Grebing et al., "Realization of a timescale with an accurate optical lattice clock", Optica* ***3****, 563 (2016).*
  - ☐ *J. Yao et al., "Incorporating an Optical Clock Into a Time Scale", IEEE Trans Ultrason Ferroelectr Freq Control* ***65****, 127 (2018).*
  - ☐ *L. Zhu et al., "Preliminary study of generating a local time scale with NIM ^{87}Sr optical lattice clock", Metrologia* ***59****, 055007 (2022).*
  - ☐ *T. Kobayashi et al., "Generation of a precise time scale assisted by a near-continuously operating optical lattice clock", Phys. Rev. Applied* ***21****, 064015 (2024).*

- ✓ **A European initiative is currently underway to develop an international timescale using optical atomic clocks.**
  - ☐ *"ROCIT: Robust optical clocks for international timescales", http://empir.npl.co.uk/rocit/*

- ✓ **An all-optical timescale has also been calculated using a silicon-cavity-based ultra-stable laser.**
  - ☐ *W. R. Milner et al., "Demonstration of a Time scale Based on a Stable Optical Carrier" Phys. Rev. Lett.* ***123****, 173201 (2019).*

NICT's Approach to an Optically Steered Timescale Signal

UTC(NICT) is generated using a hydrogen maser and a cesium clock ensemble.

18 clocks

H-Maser

Local ensemble
(calculated)

adjustment
every 8 hours

Phase stepper

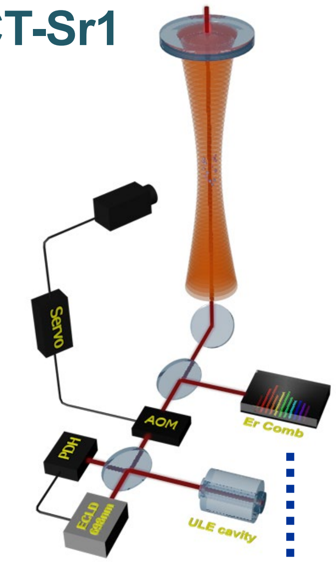
UTC(NICT)

+ 9h

Japan Standard Time (JST)

Optically steered timescale = replacing local ensemble time with optical clock data.

NICT-Sr1



measurement

H-Maser

adjustment

Phase stepper

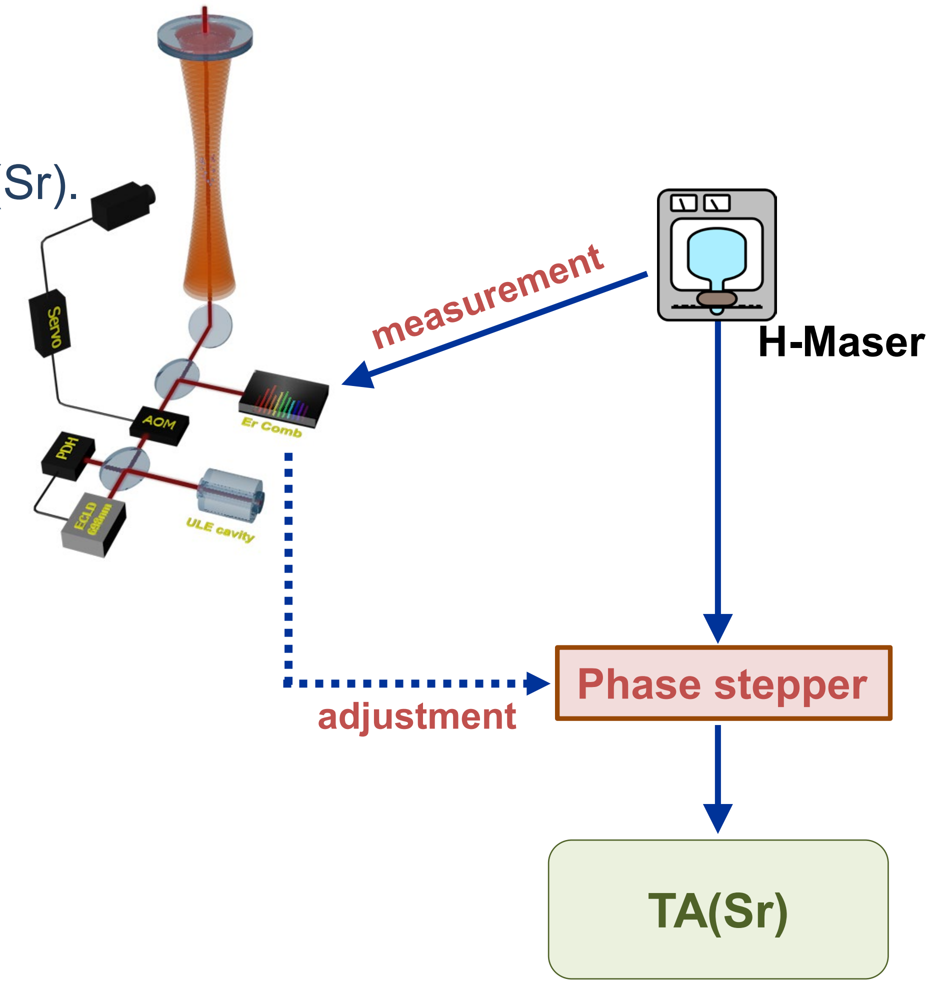
TA(Sr)

TA(Sr) is generated using data from NICT-Sr1, our strontium optical lattice clock.

NICT’s Approach to an Optically Steered Timescale Signal

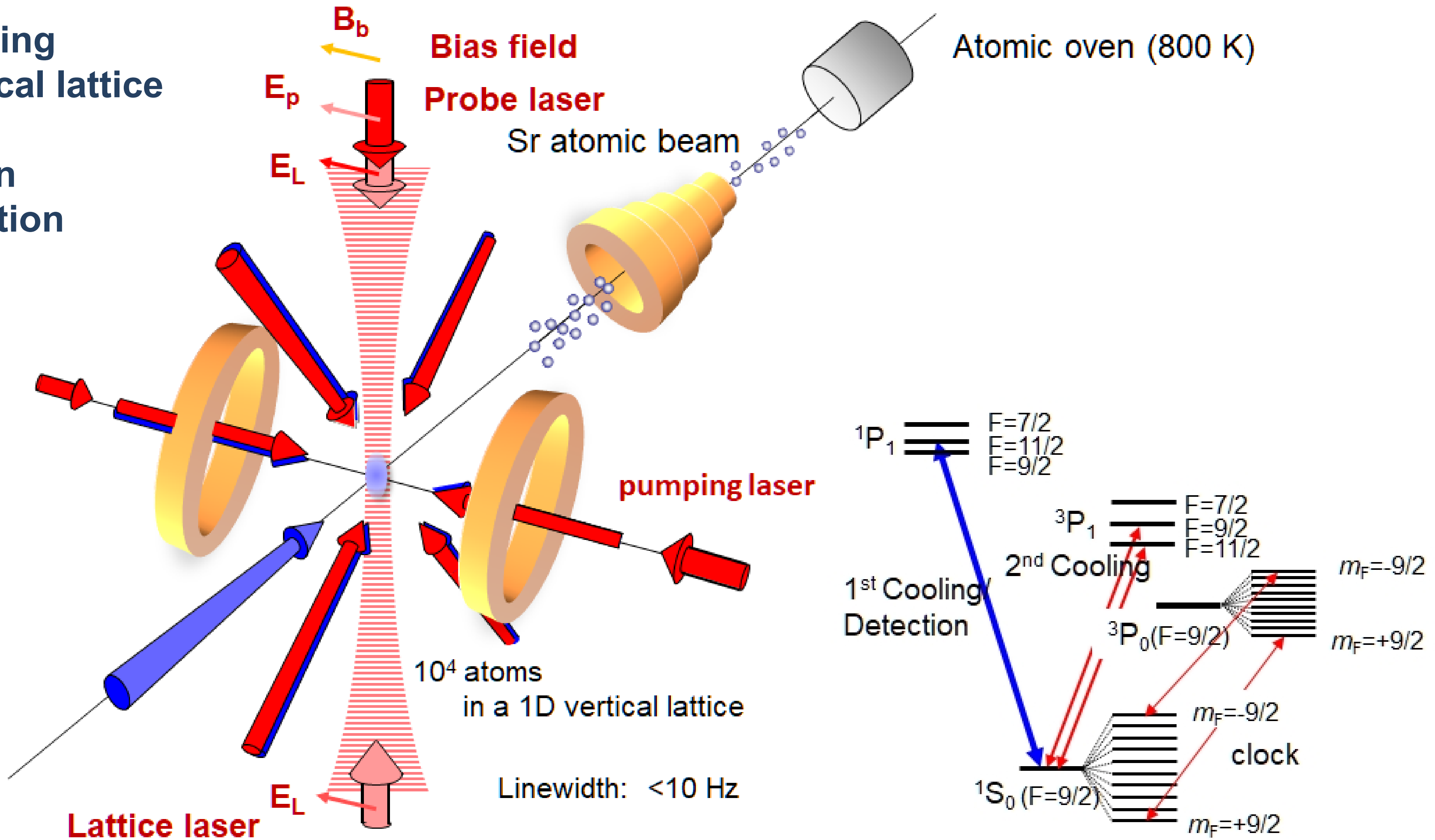
TA(Sr)

- ✓ The hydrogen maser (H-maser) serves as the source oscillator for TA(Sr).
- ✓ NICT-Sr1 is used to measure the H-maser frequency and estimate its drift rate.
- ✓ We adjust the phase stepper frequency accordingly to steer the timescale signal in real time.



How Optical Lattice Clocks Work

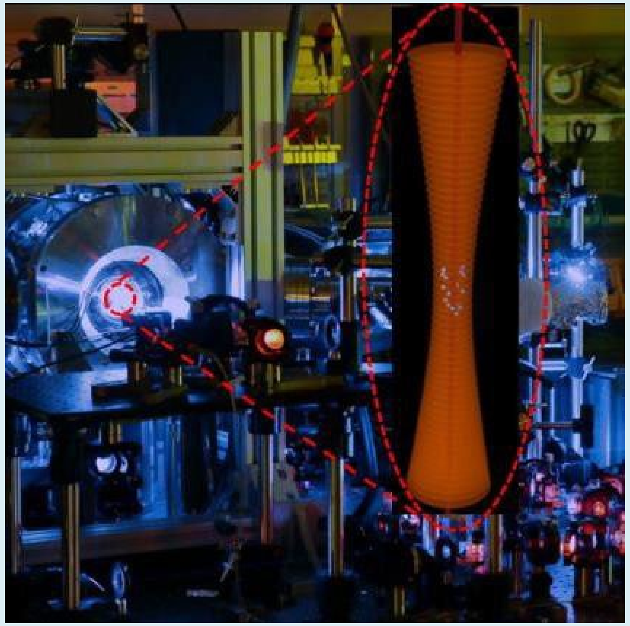
1. Laser cooling and trapping
2. Confinement in the optical lattice and state preparation
3. Clock laser interrogation
4. Detection laser illumination
5. Fluorescence detection
6. Feedback control



NICT-Sr1: NICT's Strontium Optical Lattice Clock

1. **Laser cooling and trapping**
2. **Confinement in the optical lattice and state preparation**
3. **Clock laser interrogation**
4. **Detection laser illumination**
5. **Fluorescence detection**
6. **Feedback control**

NICT-Sr1

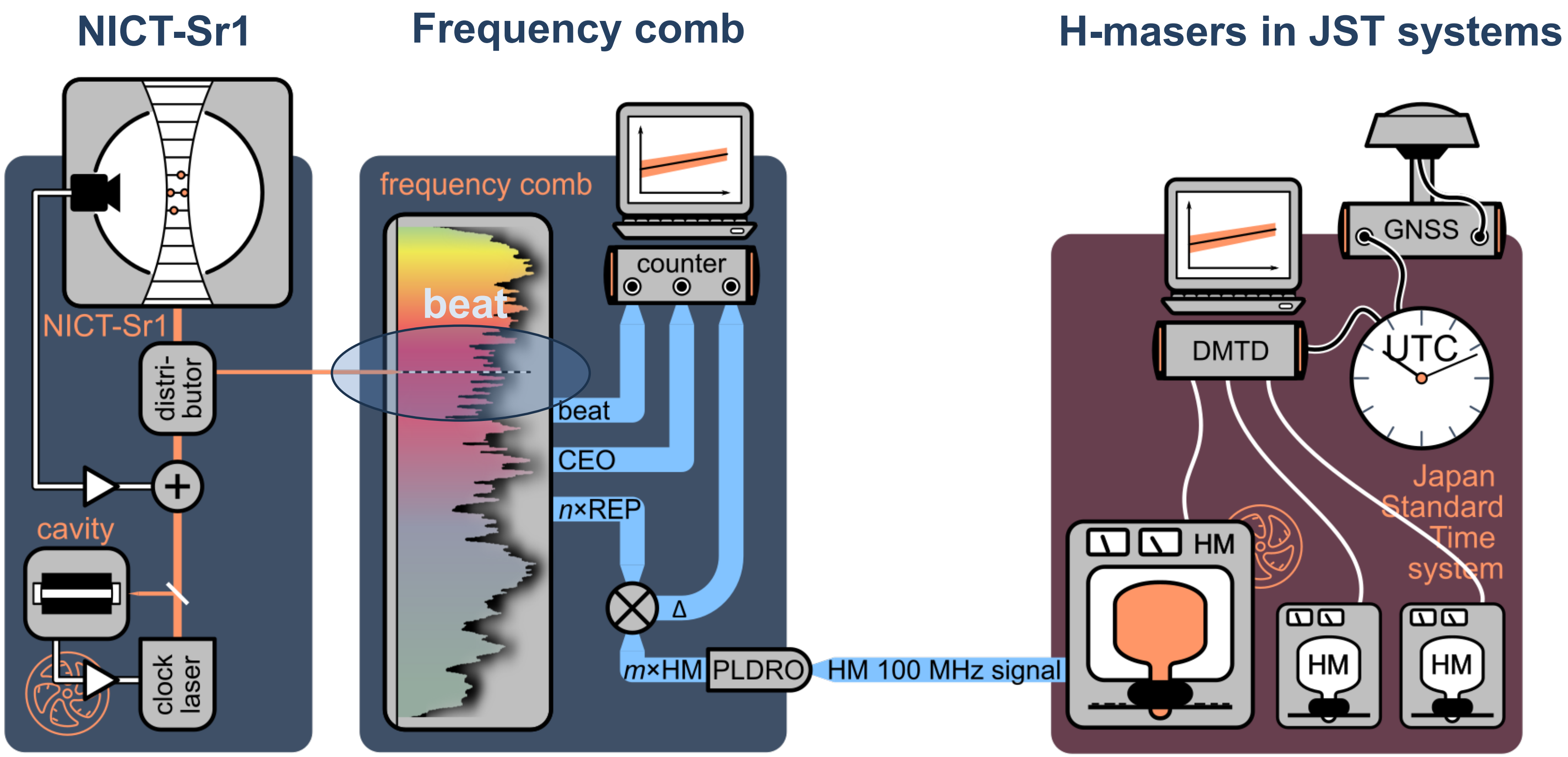


Systematic effect:	Correction (10^{-16})	Uncert. (10^{-16})
Lattice light shift	–0.02	0.53
2nd order Zeeman	5.13	0.03
Clock laser light	0.01	0.01
BBR shift	50.85	0.37
DC Stark shift	0.01	0.02
Density	0.13	0.27
Background gas	0.00	0.18
Line pulling	0.00	0.01
Total	**56.13**	**0.72**
Gravit. red shift	-83.41	0.22
SRS		1.90

6-7×10^{-17} systematic uncertainty

*Hachisu et al. 2017, Opt. Express **25**, 8511.*

Connecting Optical and Microwave Domains via Frequency Comb



- ✓ A frequency comb bridges NICT-Sr1 and the microwave domain.
- ✓ Its teeth are stabilized to the H-maser.
- ✓ Beat signal between the clock laser and the nearest comb tooth enable optical-to microwave frequency comparison.

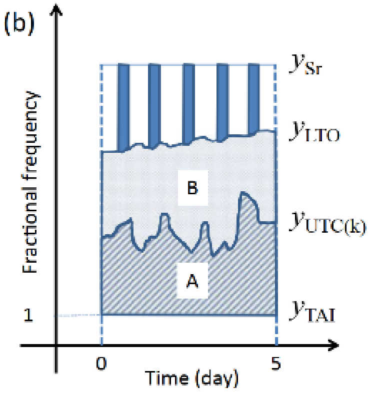
How Often and How Long Do We Need to Run a Sr Clock ?

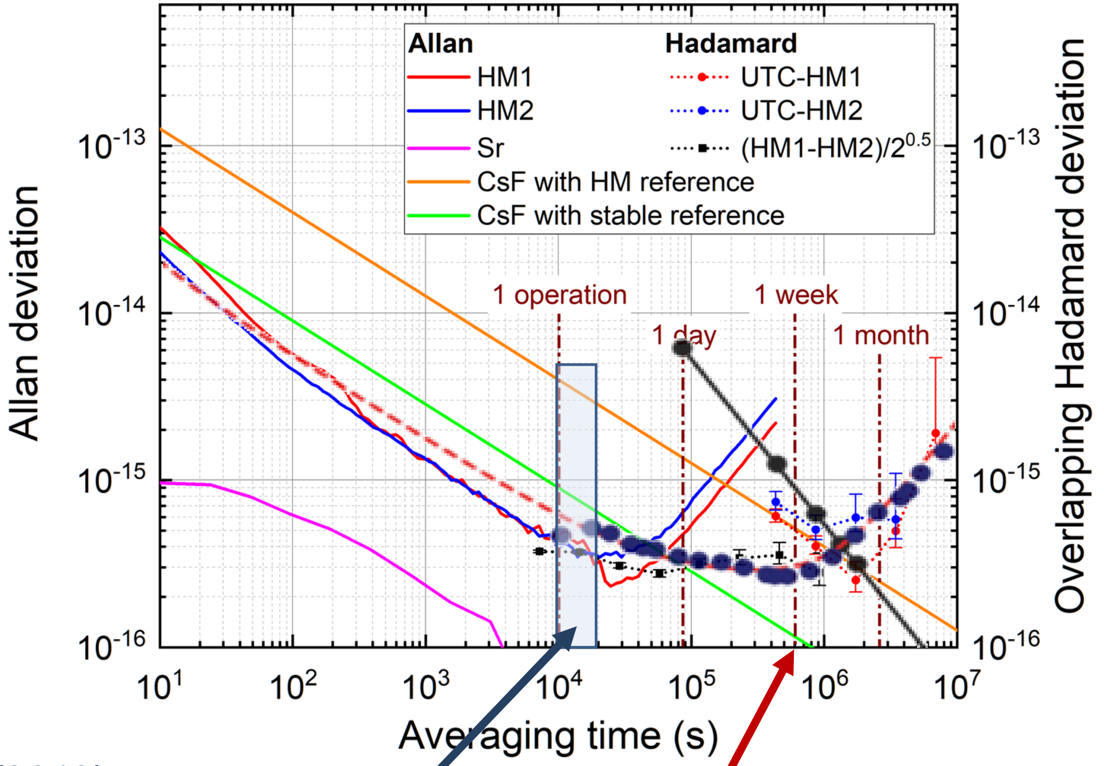
Idea:
NICT's H-maser is stable enough that we can determine its mean frequency **through periodic checks, rather than continuous measurement.**

Japanese Journal of Applied Physics **54**, 112401 (2015)
http://dx.doi.org/**10.7567/JJAP.54.112401**

Intermittent optical frequency measurements to reduce the dead time uncertainty of frequency link

Hidekazu Hachisu and Tetsuya Ido





See also (NIST, 2019):
Yao et al. "Optical-Clock-Based Time scale", Phys. Rev. Applied ***12****, 044069 (2019).*

- ✓ We performed measurements over 3 to 8 hours to evaluate the H-maser frequency with an uncertainty of only a few parts in 10^{-16}.
- ✓ This H-maser maintains this level of stability over 1-2 weeks.
- ✓ We measure intermittently—about once a week, typically for 3-8 hours.

One measurement

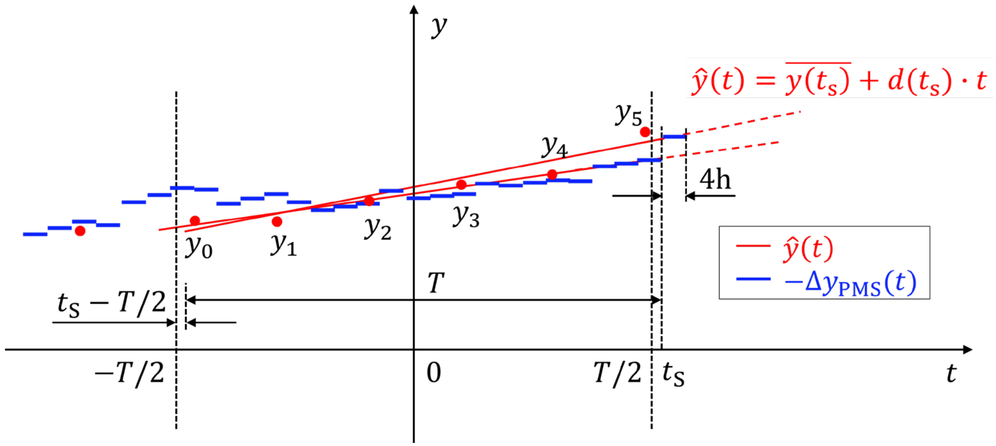
Break between measurements

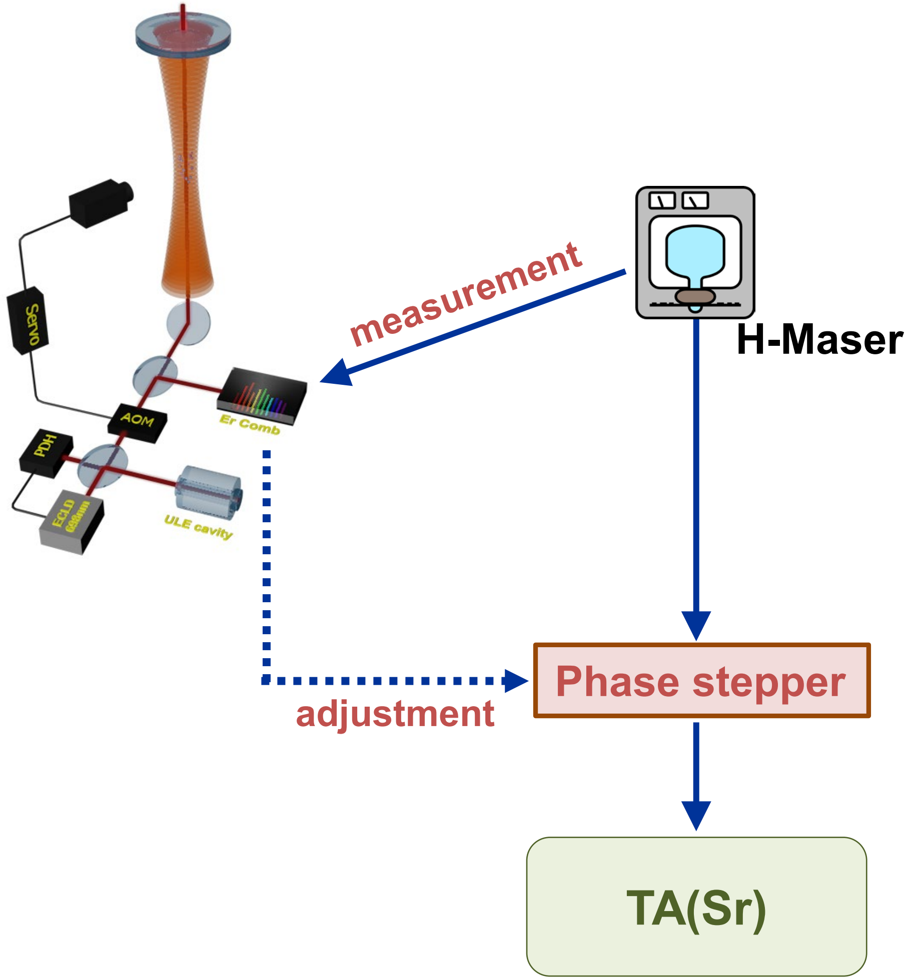
How NICT Implements an Optically Steered Timescale

First demonstrated in 2016:
H. Hachisu et al., "Months-long real-time generation of a time scale based on an optical clock", Sci. Rep. ***8****, 4243 (2018).*

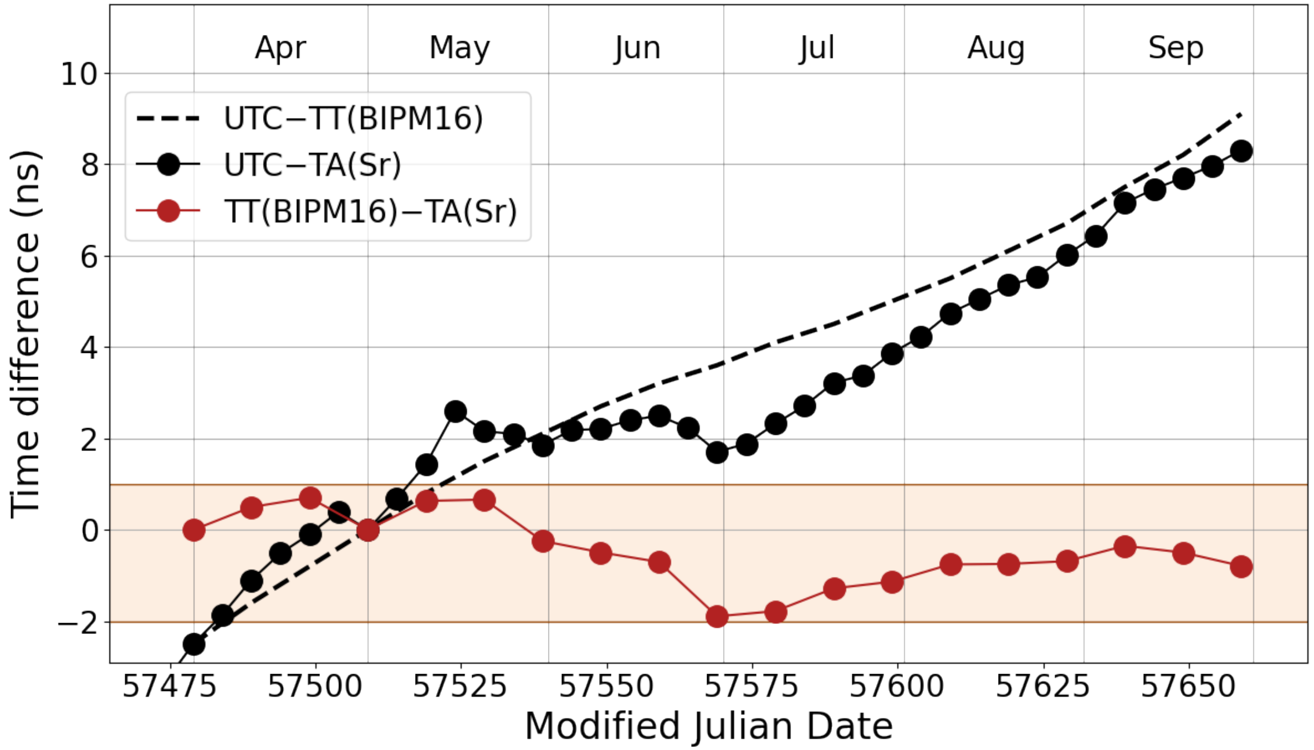
Overview:
NICT's optically steered timescale uses periodic Sr clock measurements to estimate and correct the drift of a H-maser.

Key parameters for optical steering of TA(Sr):
- ✓ Linear drift estimation interval: T = 25 days
- ✓ Number of measurement points in interval T: Typically 4 or 5 (e.g., one Sr clock operation per week or more frequently)
- ✓ Drift rate update frequency: Every 4 hours





Comparing UTC and TA(Sr)



Adapted from H. Hachisu et al.,Sci. Rep. ***8****, 4243 (2018).*

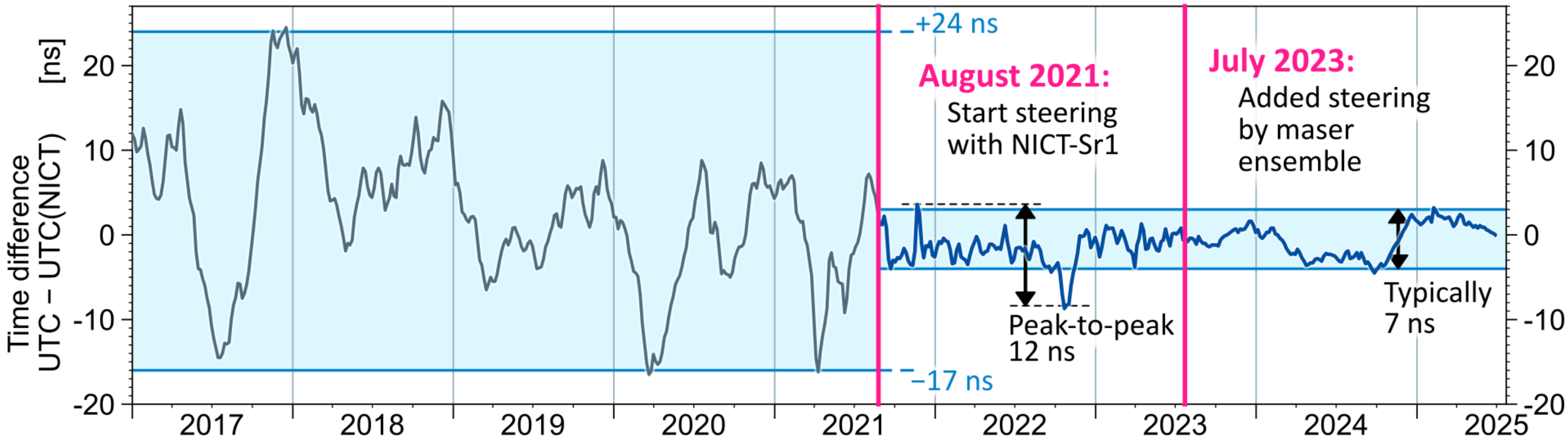
- ✓ **TA(Sr)**: Sr-based timescale
- ✓ **TT(BIPM16)**:
  A post-processed timescale incorporating all data from primary frequency standards up to the year 2016

- Peak-to-peak time difference remained within 3 ns over a 5-month period
- Stability 4×10^{-16} @20days

Current sophisticated realizations UTC(*k*) are adjusted to stay within $\pm$5 ns of UTC.

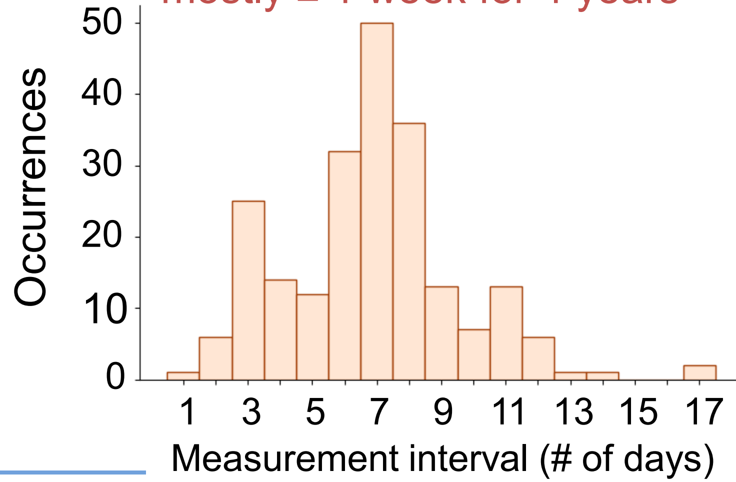
Next step: Generate UTC(NICT) with precision comparable to cesium-fountain-steered timescales — even using intermittent optical clock measurements

Generating UTC(NICT) using NICT-Sr1



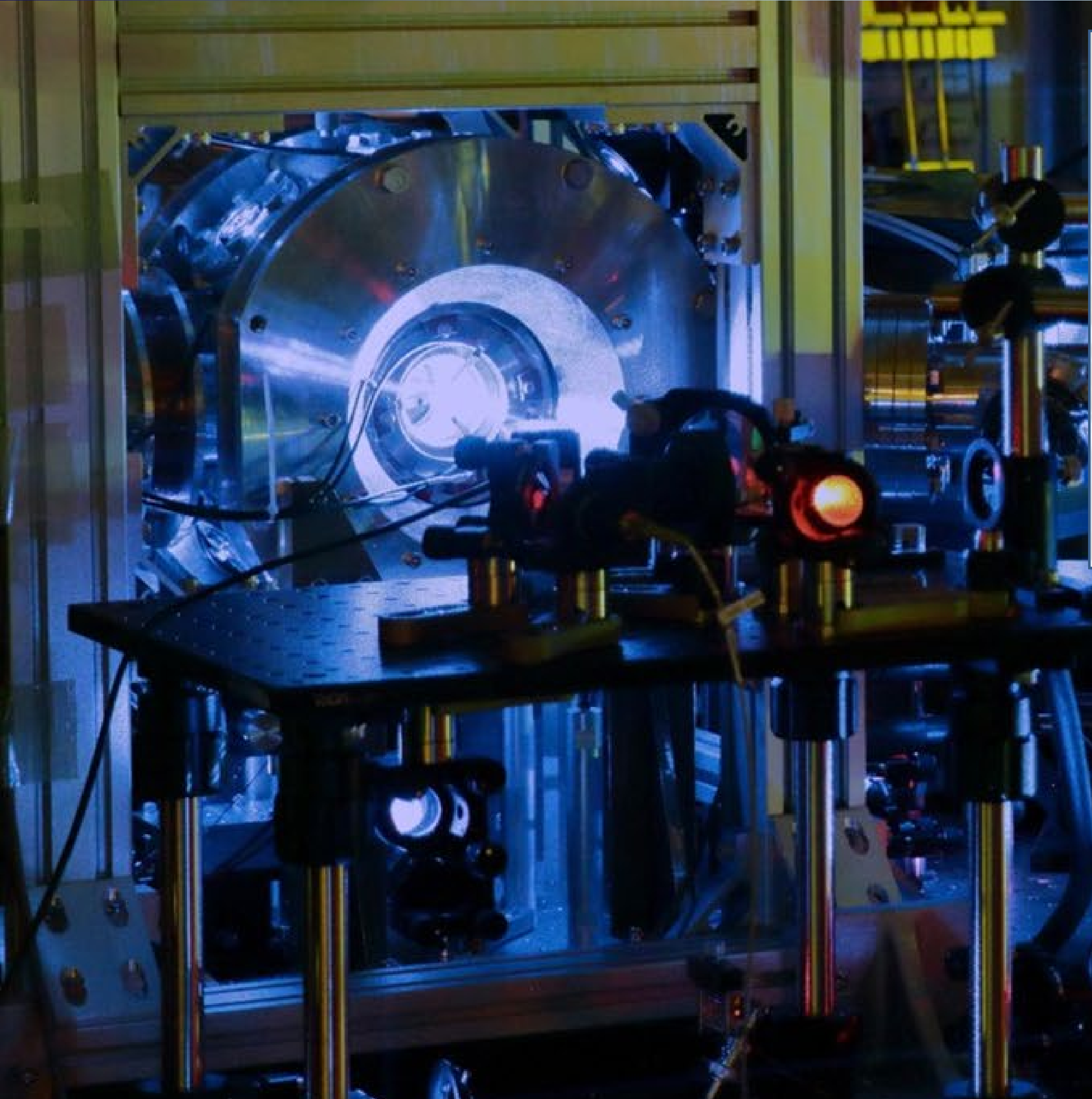
Extended from H. Hachisu, et al., J. Phys.: Conf. Ser. ***2889****, 012018 (2024).*

Measurement Interval
mostly ≤ 1 week for 4 years



- ✓ Since August 2021, UTC(NICT) has been steered with reference to an optically steered timescale based on NICT-Sr1.
- ✓ This reduced the deviation from UTC to typically just 7 ns peak-to-peak over more than four years.
- ✓ The improved stability reflects the performance of TA(Sr), now serving as the reference.
- ✓ The ensemble consisted of commercial cesium clocks until July 2023.
- ✓ Stability was further enhanced by adding H-masers.

Summary



- ✓ NICT was the first to generate a real local timescale signal based on an optical clock. A strontium optical lattice clock is used to intermittently evaluate the timescale more than once a week.
- ✓ Since August 2021, Japan Standard Time (JST) has been generated using this optically steered timescale — now maintained for four years.

If you have any questions, feel free to ask during the coffee break or to contact me by email after the session.
You can reach me at: hachisu@nict.go.jp