UTC(k) steered by intermittent operation of an optical clock

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Outline

UTC(k) generation using an optical clock

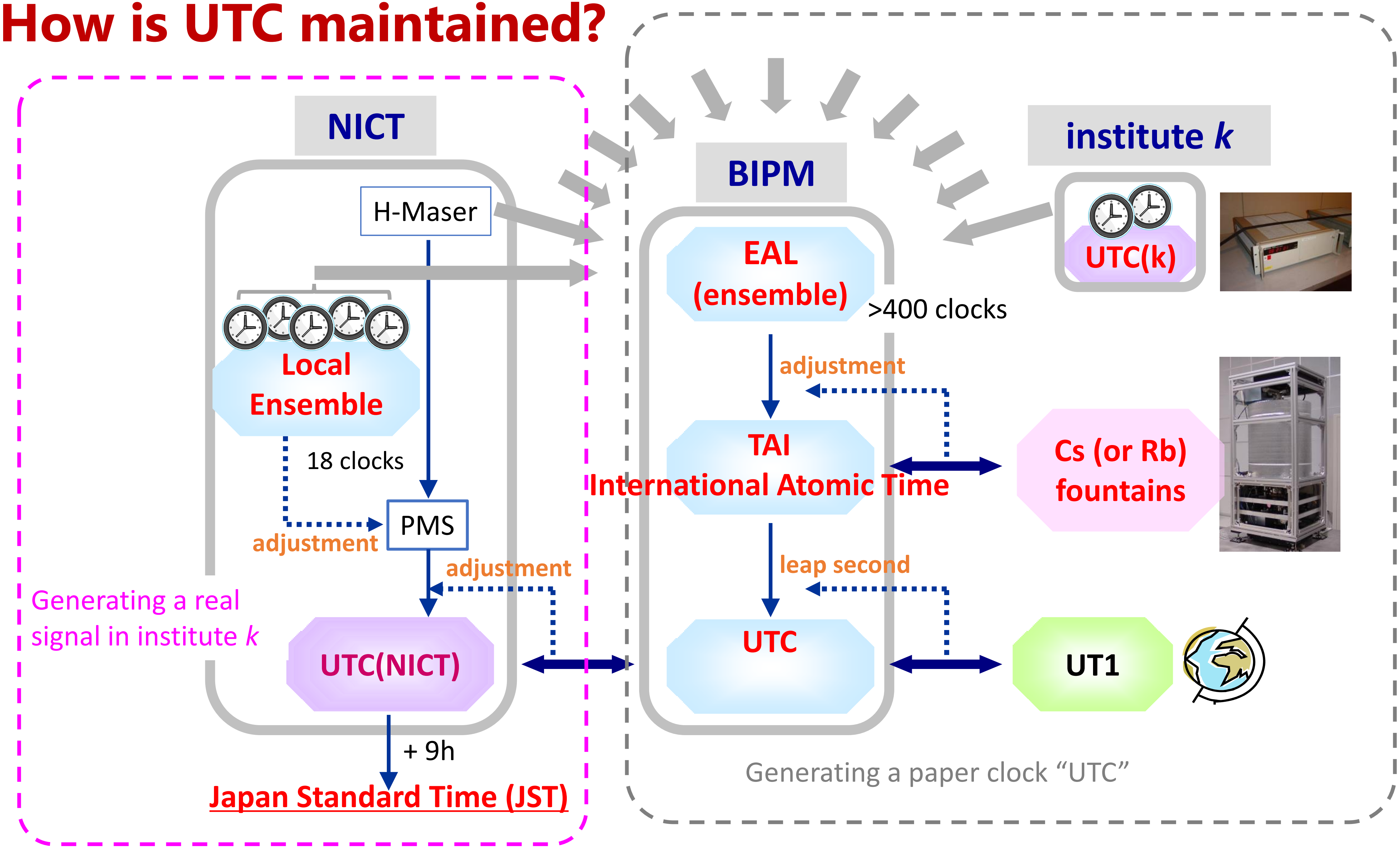
- UTC(k) : real signal generated in laboratory k
- Optically steered timescale (1):
  Source oscillator + Frequency reference
- Optically steered timescale (2):
  Source oscillator + MW clock ensemble + Frequency reference
  - Optically steered UTC(NICT) for 2 years
- Recent improvements

Option 2 in the redefinition of the SI second

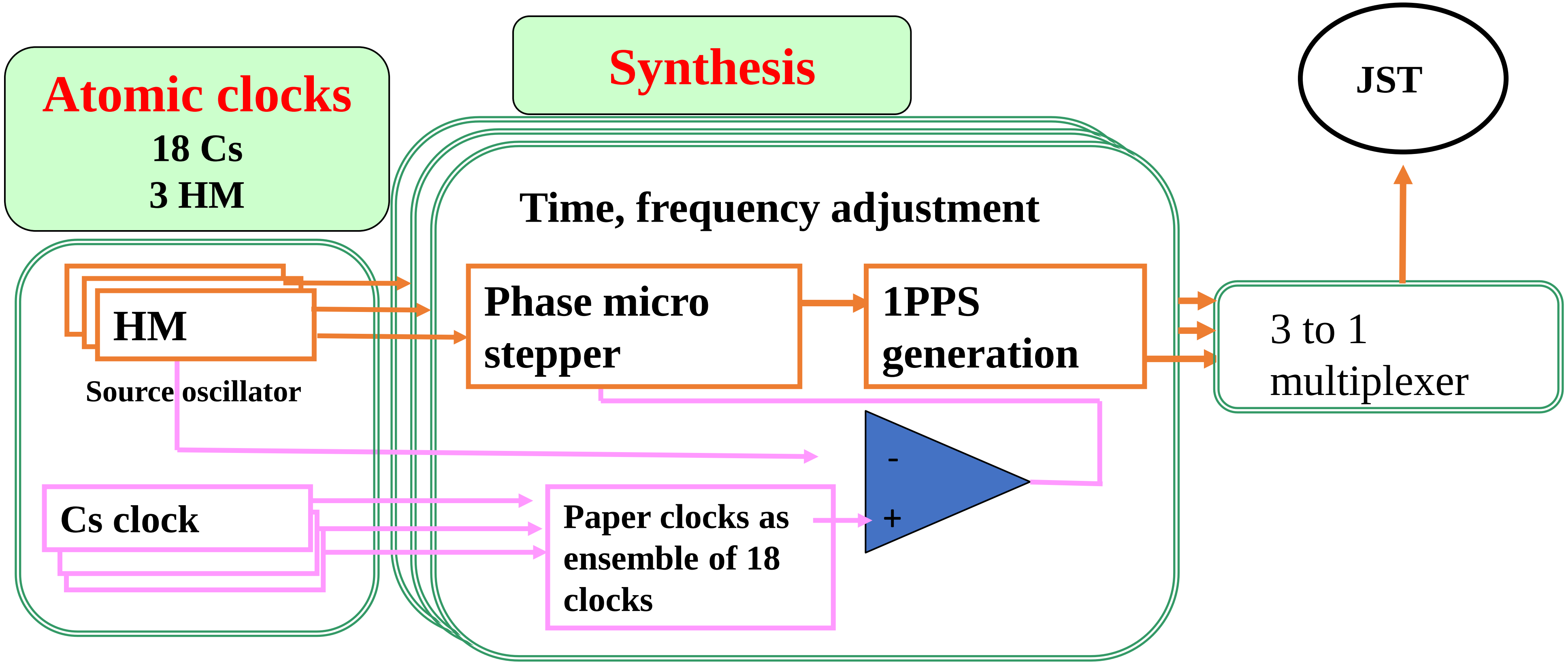
- Graphical picture of the option 2a and 2b for the redefinition of the SI second

UTC(k) generation using an optical clock

How is UTC maintained?



JST generation



HM frequency was steered to ensemble of 18 Cs clock

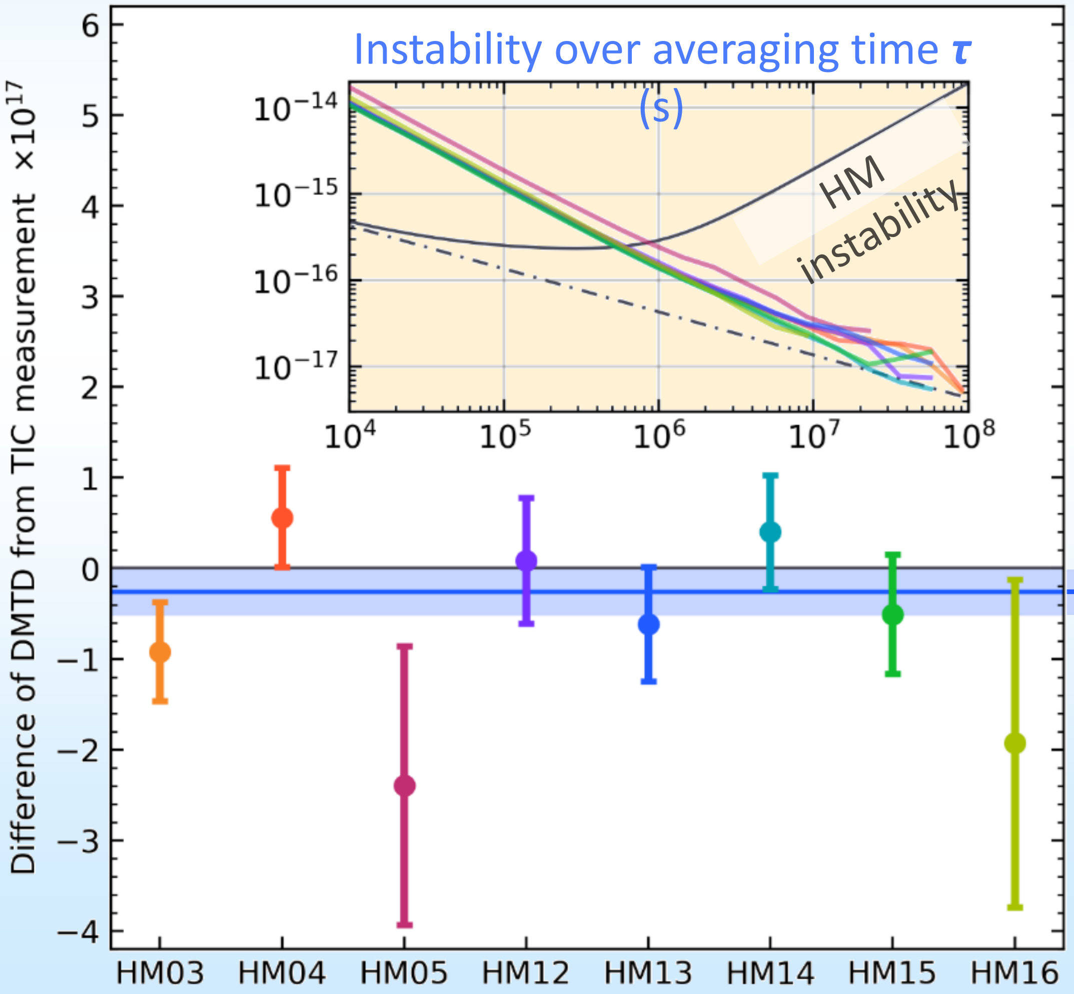
DMTD system performance

- Flywheel HM – UTC(NICT)
✓ HM rf signal transfer
✓ comb up-conversion

We similarly examine the performance of the Japan Standard Time system **dual-mixer time-difference** system.

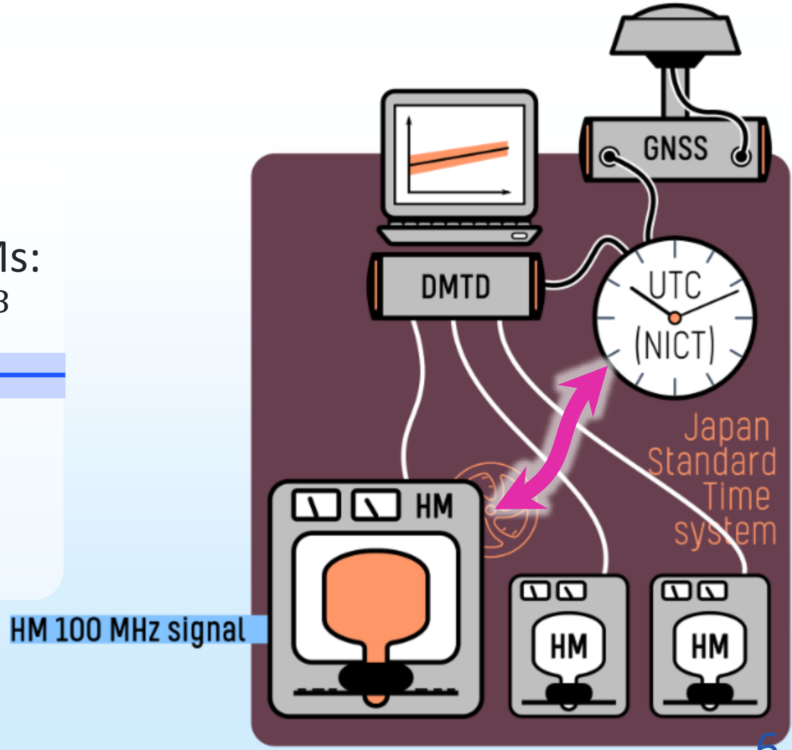
Constant errors are bounded by comparing DMTD measurement against a time interval counter (TIC).

Agreement of TIC and DMTD

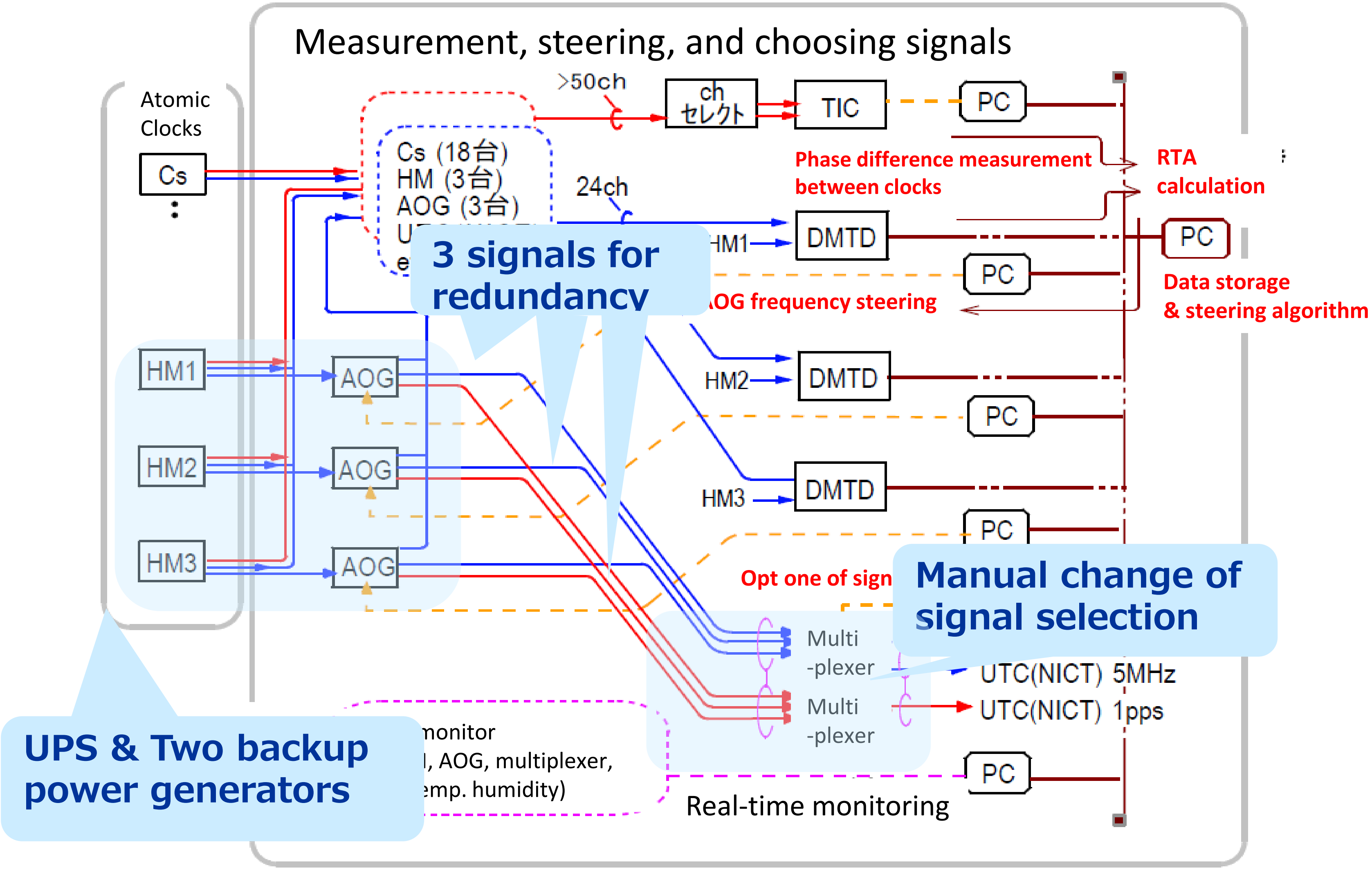


Frequency difference since 2012, over 8 HMs: $(-2.6 \pm 2.7) \times 10^{-18}$

We expect persistent frequency errors $< \mathbf{3.7 \times 10^{-18}}$

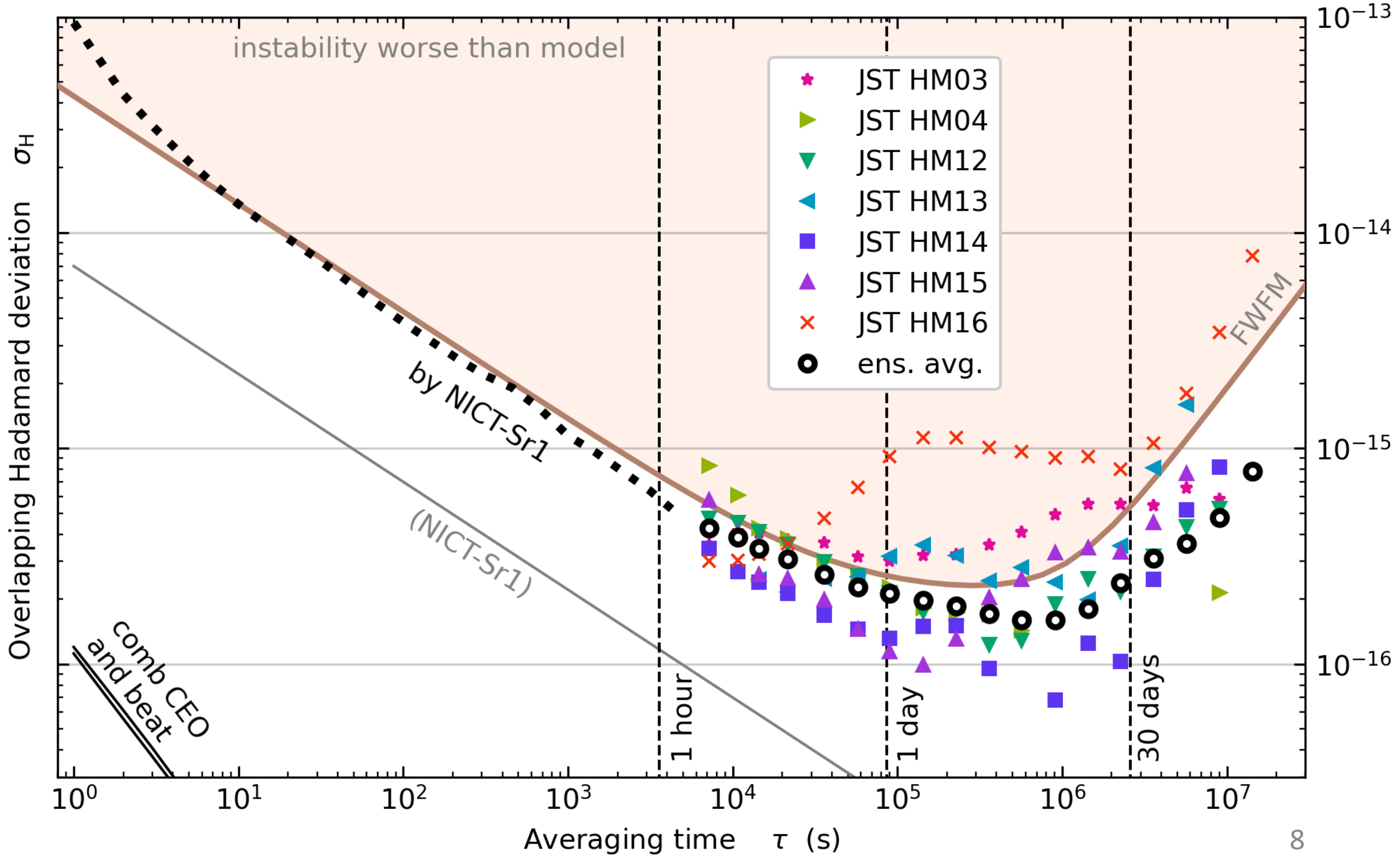


Reliability (Power & Signals)



Hydrogen masers at NICT

- NICT operates multiple HMs that has Hadamard deviations at the 10^{-16} level.
- Mid 10^{-16} level of Hadamard deviation extends to 10 days or more.
- Mote than half of HMs reach less than 2×10^{-16} at the bottom.



Japan Standard Time before 2020

Timescale generation

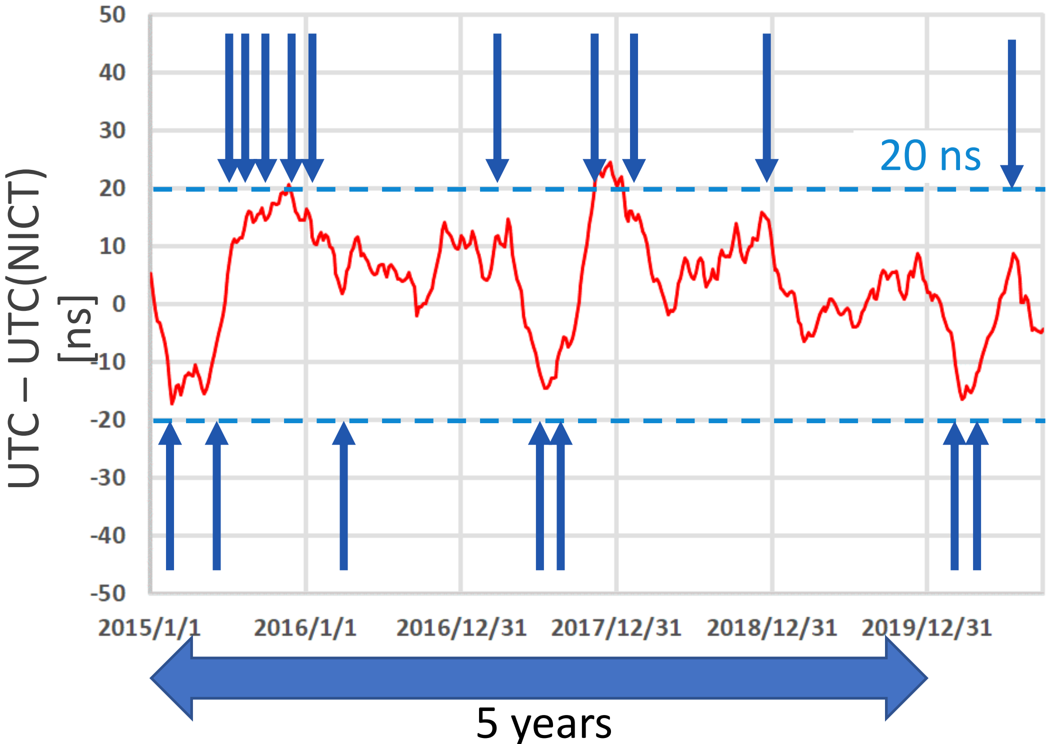
- One hydrogen maser is source oscillator for UTC(NICT)
- Two more masers serve as backup.
- An ensemble of 18 cesium 5071A clocks steers the timescale.

JST system

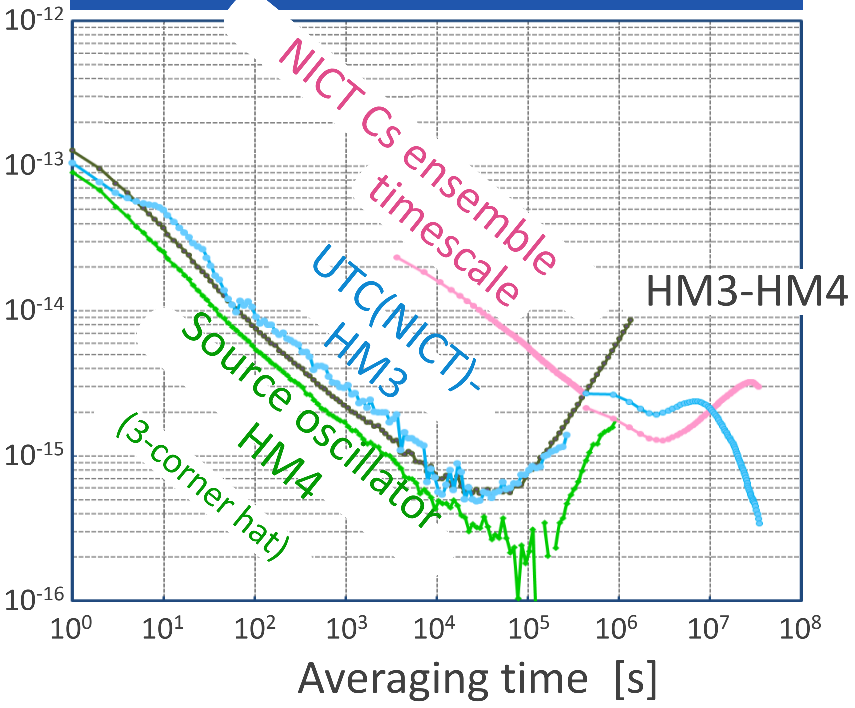
backup generator

Behavior of UTC(NICT)

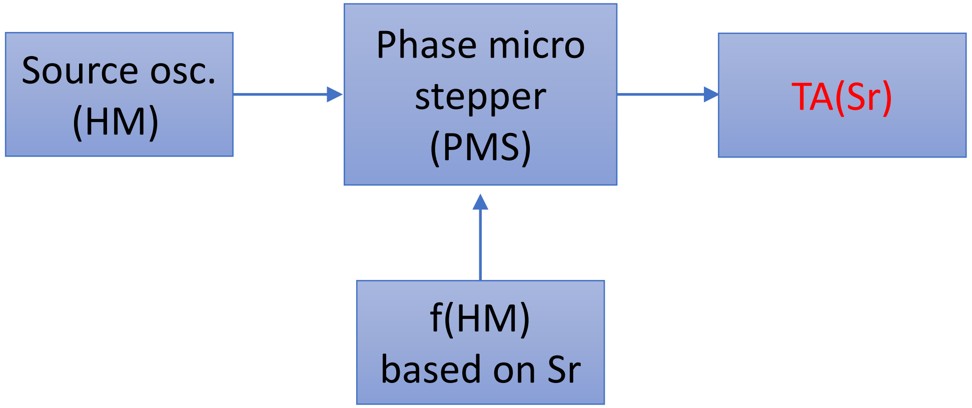
- The deviation from UTC is typically less than 20 ns.
- Instability is 2×10^{-15} over 10 to 30 days.

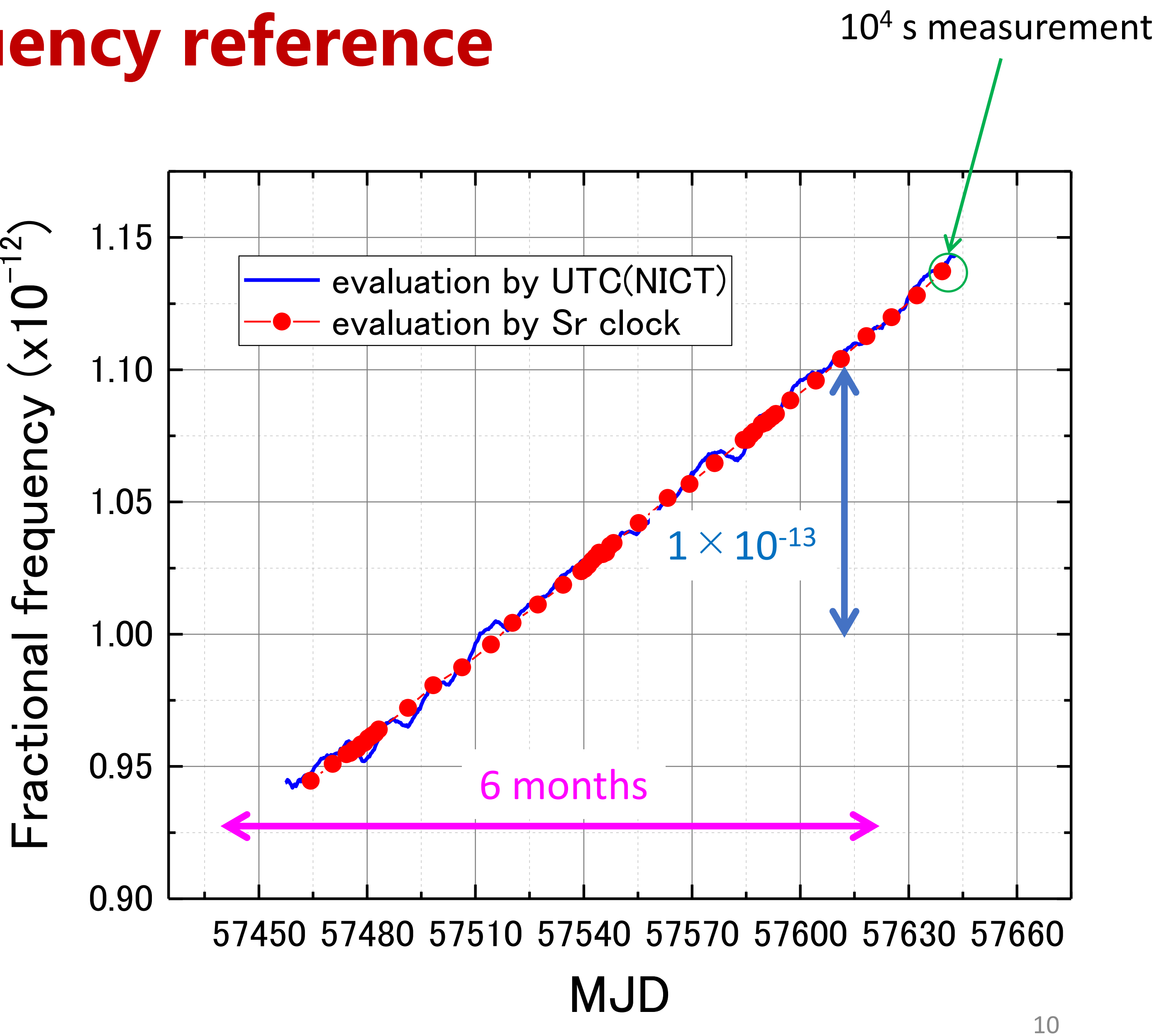


Allan deviation

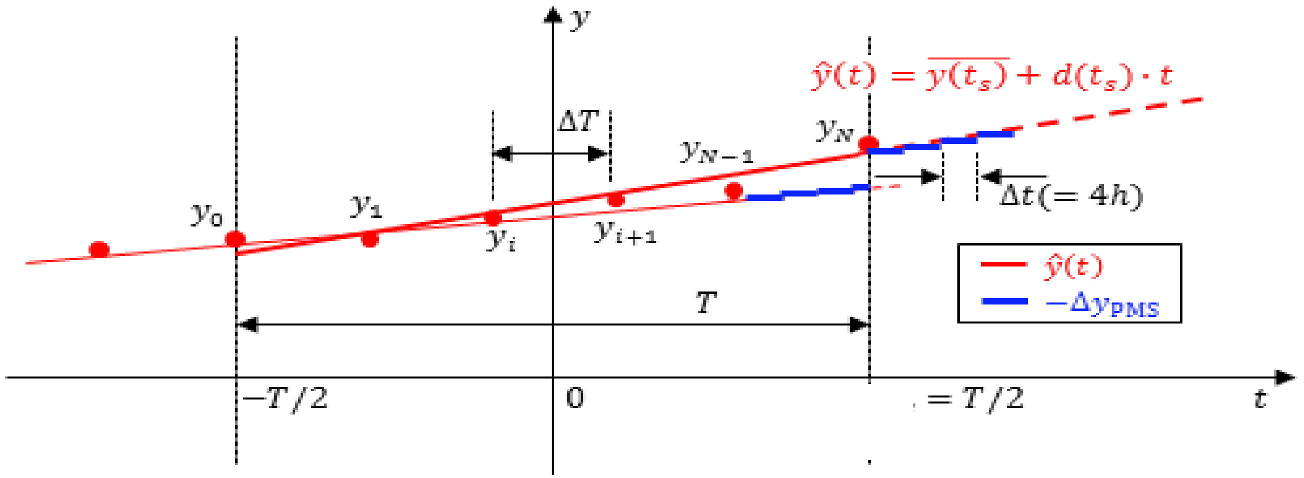


Optically steered timescale in 2016: Source oscillator + Frequency reference





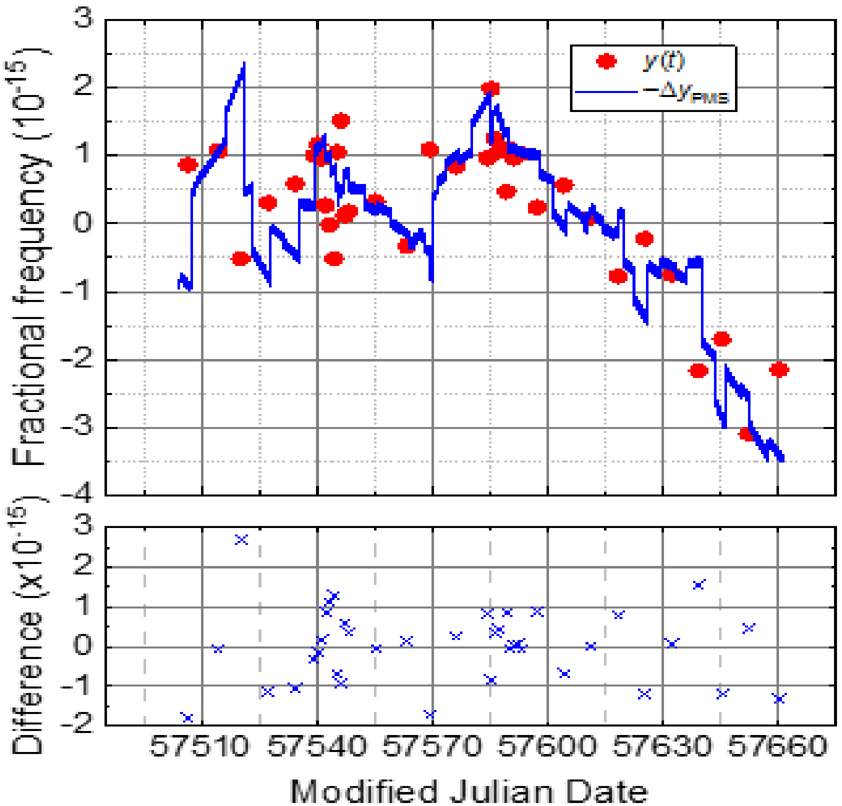
- TA(Sr): Frequency and drift rate of HM signal is adjusted with reference to Sr
- Adjustment of PMS offset frequency every 4 hours
- No servo to reduce the time offset $\mathrm{UTC} - \mathrm{TA(Sr)}$



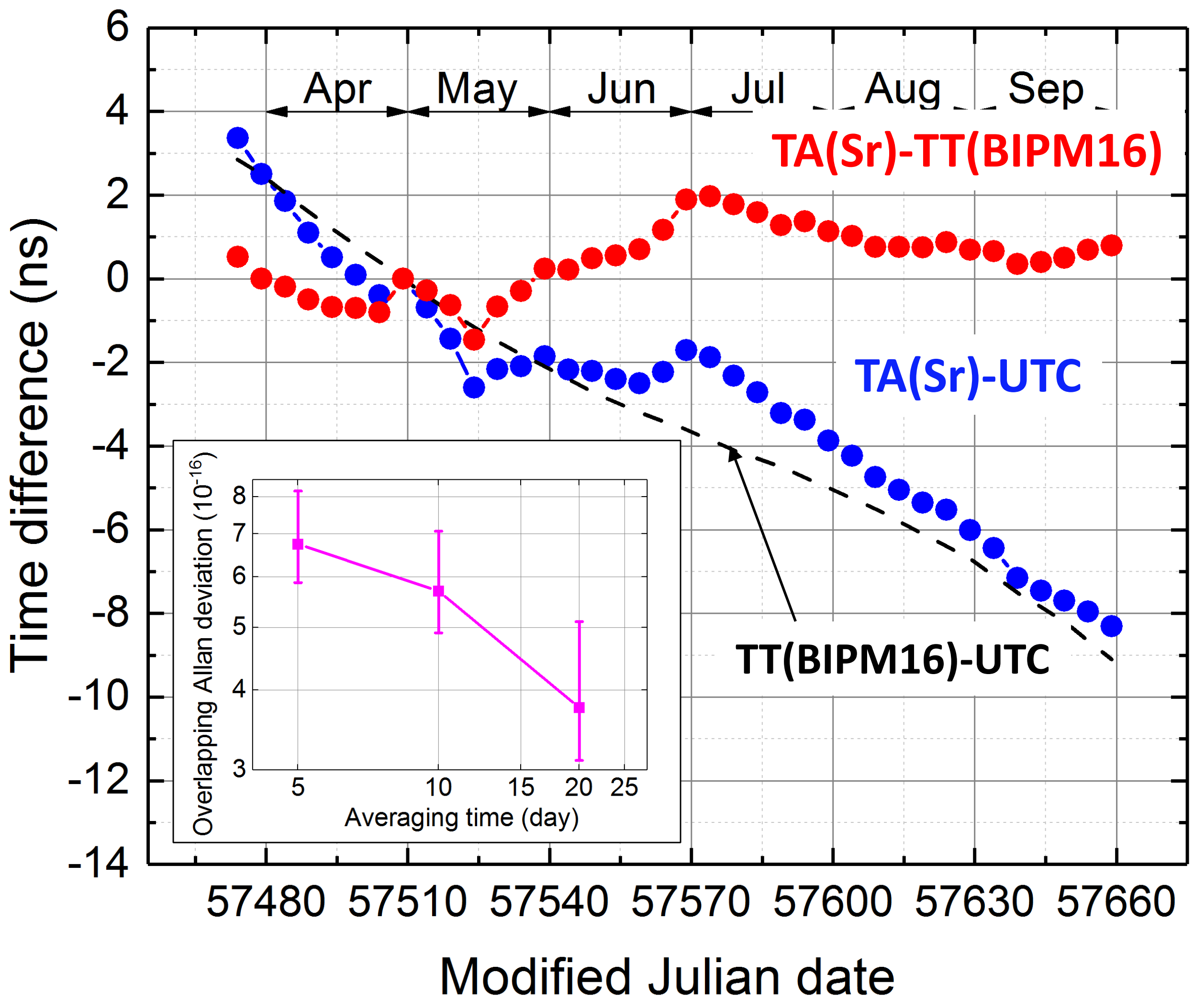
Interval for the drift estimation: T=25days

Number of Optical frequency standard (OFS) operation in T : N+1 >4
(once per week or more frequently)

One HM free evolution time: $\Delta T = T/N$



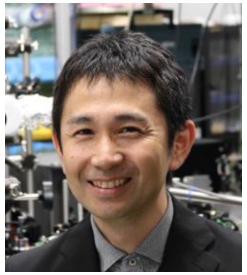
Comparison against UTC & TT(BIPM16)



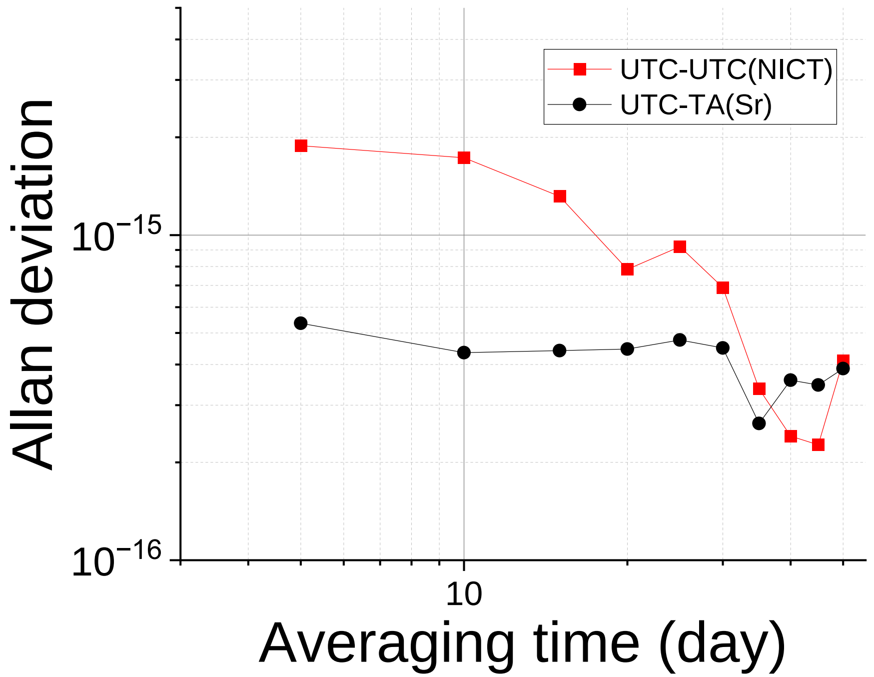
- the frequency offset of UTC is clearly identified.

  Phase difference against TT(BIPM16)
  < 1ns after 5months

  Stability 4e-16 @ 20 days



H. Hachisu



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

Upgrade of UTC(NICT) in 2021


F. Nakagawa


K. Imamura

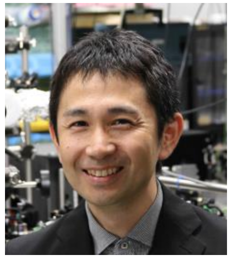

Y. Hanado

<u>2006</u>

- JST system built in 2006 with rich redundancies for reliability.
  - Three independent HMs signals are steered to ensemble clocks made of 18 Cs
  - 3 DMTD & 1 TIC for reliable measurement of clock phase differences

<u>2016</u>

- Test operation of a Sr-steered timescale (1HM + Sr) showed great potential in accuracy.


H. Hachisu

<u>2020</u>

- Reliability of Opt.-> MW conversion improved. Monitor, control, and evaluation have become systematic. Redundancy in various parts established.

→ Reliable operation of a Sr lattice clock once per week now feasible.


N. Nemitz

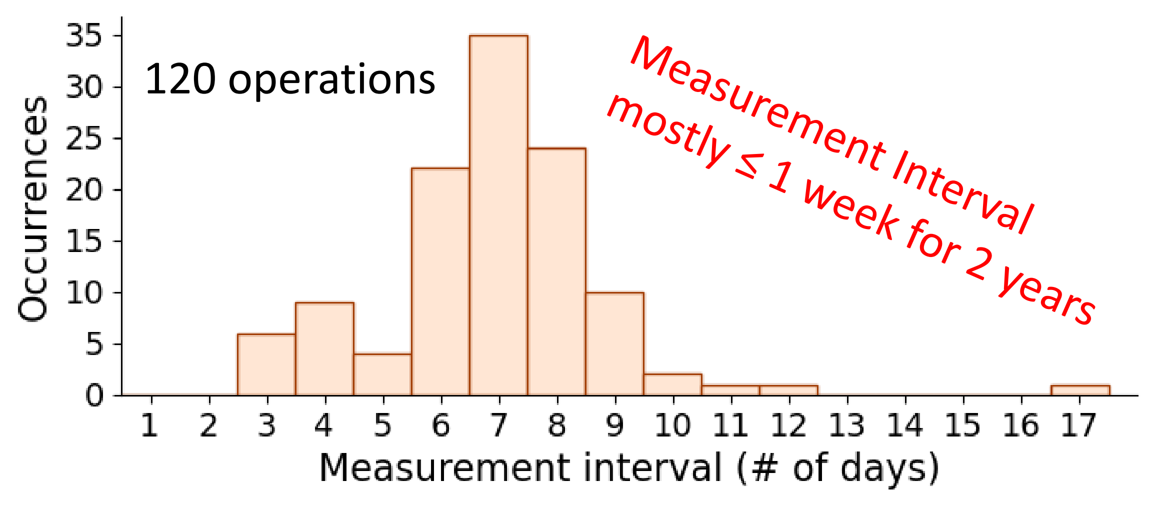
2021 – UTC(NICT) is finally steered by NICT-Sr1

Strategy

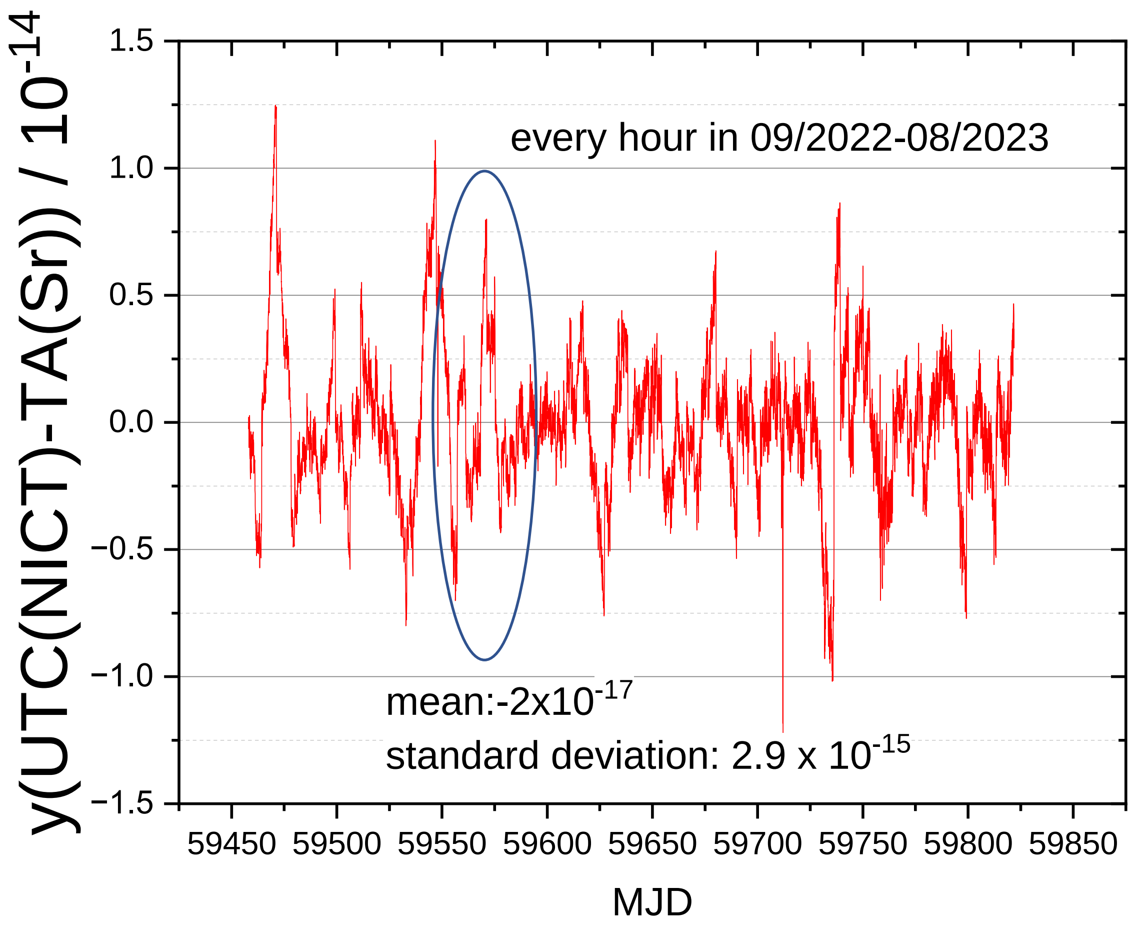
- To keep the benefit of reliability in legacy system…
  - Keep the steering of 3 HM signals to Cs ensemble

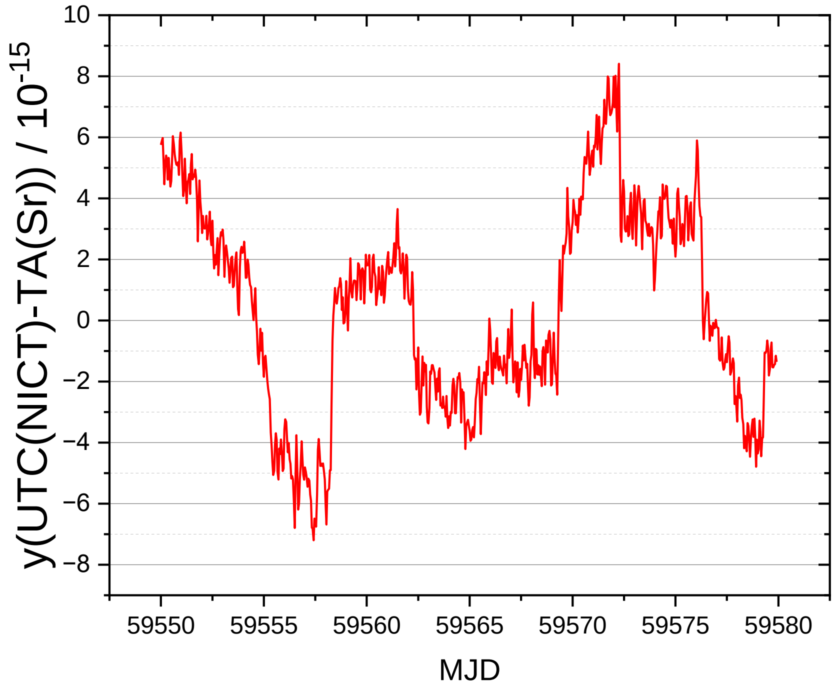
    →Occasional adjustment of the parameter of frequency offset with respect to Cs ensemble timescale
- To keep the intermittent operation of the strontium lattice clock (once per week)
  - →Leaves four (or more) working days for any necessary. Reduced operation time to extend the durability

- Operations once per week or more has continued since September 2021, and is still ongoing.



Recipe of steering



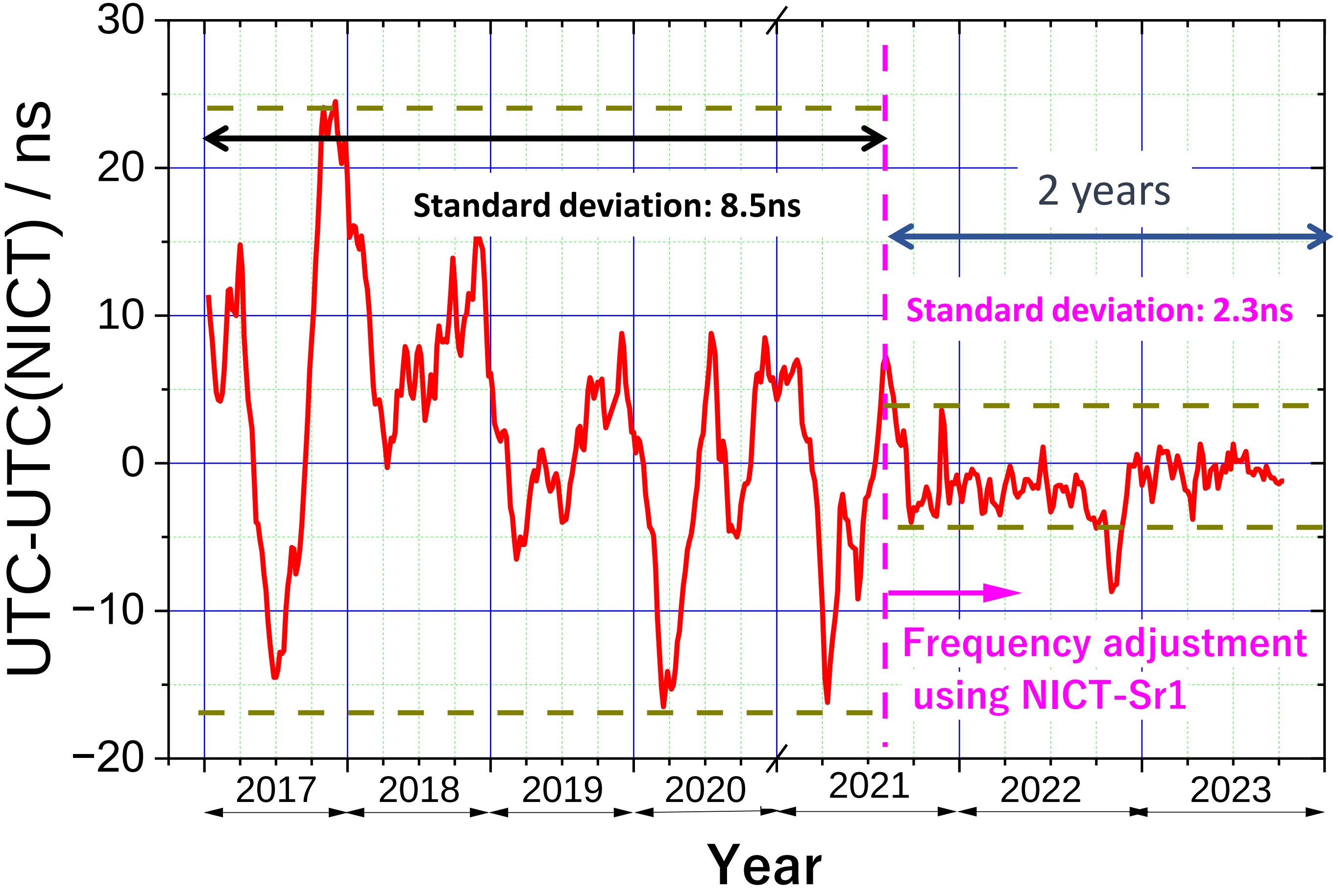


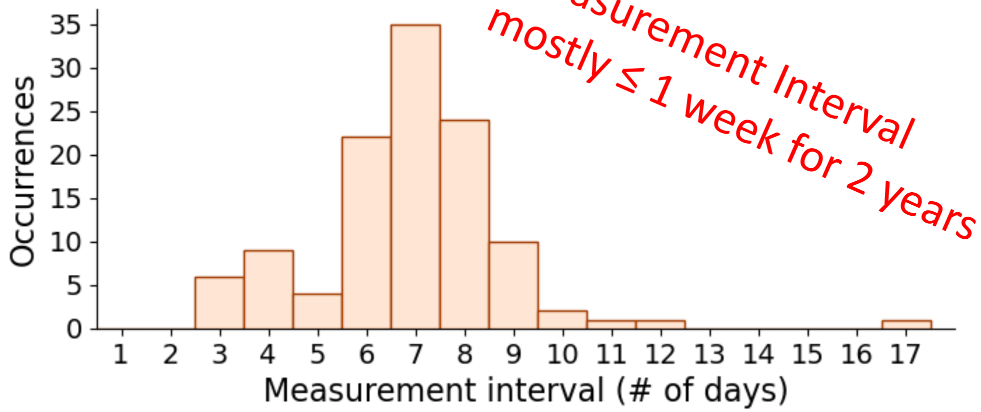
Frequency adjustment of UTC(NICT) twice per week to remove y(UTC(NICT)-TA(Sr)) in the one past day

The instability of Cs ensemble often requires >3e-15 adjustment

Time difference ΔT=UTC(NICT)-TA(Sr) gradually removed by additional fractional frequency adjustment of ΔT/(60 days)

Steering using optical clocks: before & after





Measurement Interval mostly ≤ 1 week for 2 years

- Incorporation of Sr reduced the fluctuation to 1/4.
- The magnitude of the reduced fluctuation reflects the stability of mean timescale composed of commercial Cs clocks

(Poster No. 110)

Incorporation of HMs to TA

H. Ito

- HMs have been used only as source oscillators.
  But predictions of the frequency drift in HMs allow us to incorporate HMs to the ensemble clocks.

- BIPM did similar improvement in early 2010s*. EAL incorporate the 2nd-order term (frequency drift) of atomic clocks

  → Cs clocks have lost the weight, but HM gained the weight

Note that NICT prefers to depend on our own clocks as much as possible for resilience against the GNSS non-availability

- Similar strategy possible by adding HMs to ensemble clocks as well as changing the dedrifting process in mean free time scale.

*G. Panfilo, et al., Metrologia **49**, 49 (2012)
G. Panfilo et al., Metrologia **51**, 285 (2014)

Detrend term

Actual calculation (an example)

- **y (rate) and w (weight) define TA's character**

$$\hat{x}_i(t_k) = x_i(t_{k-1}) + \hat{y}_i(t_k)\cdot(t_k - t_{k-1}) \quad \ldots(8)$$

$$x_s(t_k) = \sum_i w_i(t_k)\{\hat{x}_i(t_k) - X_{is}(t_k)\} \quad \ldots(6)$$

$$x_i(t_k) = x_s(t_k) + X_{is}(t_k) \quad \ldots(9)$$

:Measured *:Predicted* *:Output*

:Calculated from x_i

Clock rate

$$\hat{y}_i(t_k) = \frac{x_i(t_{k-1}) - x_i(t_{k-1} - T)}{T}$$

Linear prediction
based on the past duration T
with respect to **TA itself**

Could be self divergent

- **Suited method and value for the purpose are important.**

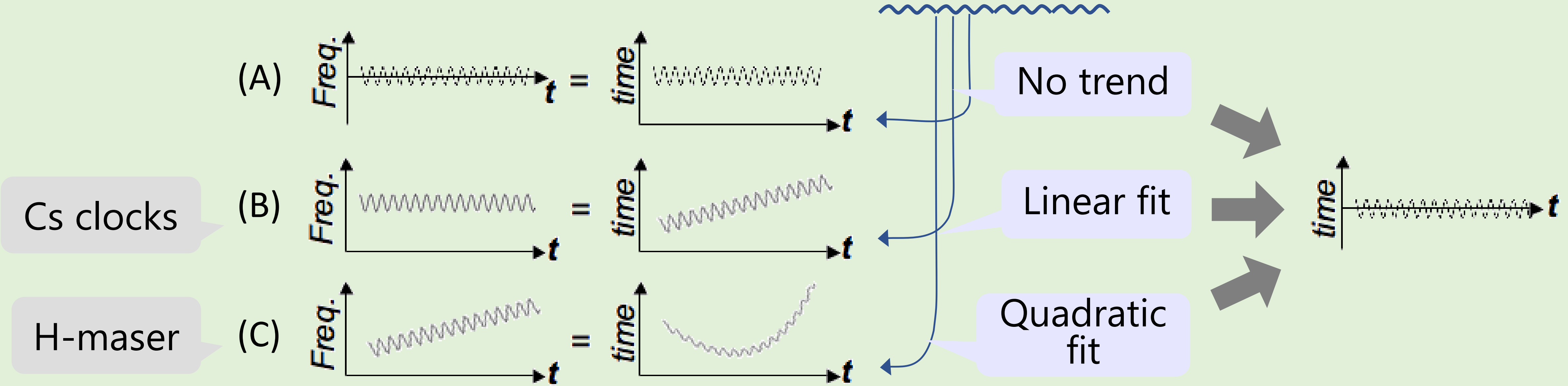
From Y. Hanado, IFCS-EFTF 2023 tutorial (2023)

Actual calculation (an example)

■ Variation of de-trending

- **The optimal way to detrend depends on the clock's behavior.**

$$\hat{\boldsymbol{x}}_{\boldsymbol{i}}(\boldsymbol{t}_{\boldsymbol{k}}) = \boldsymbol{x}_{\boldsymbol{i}}(\boldsymbol{t}_{\boldsymbol{k-1}}) + \textbf{detrend term} \quad ...(8)$$



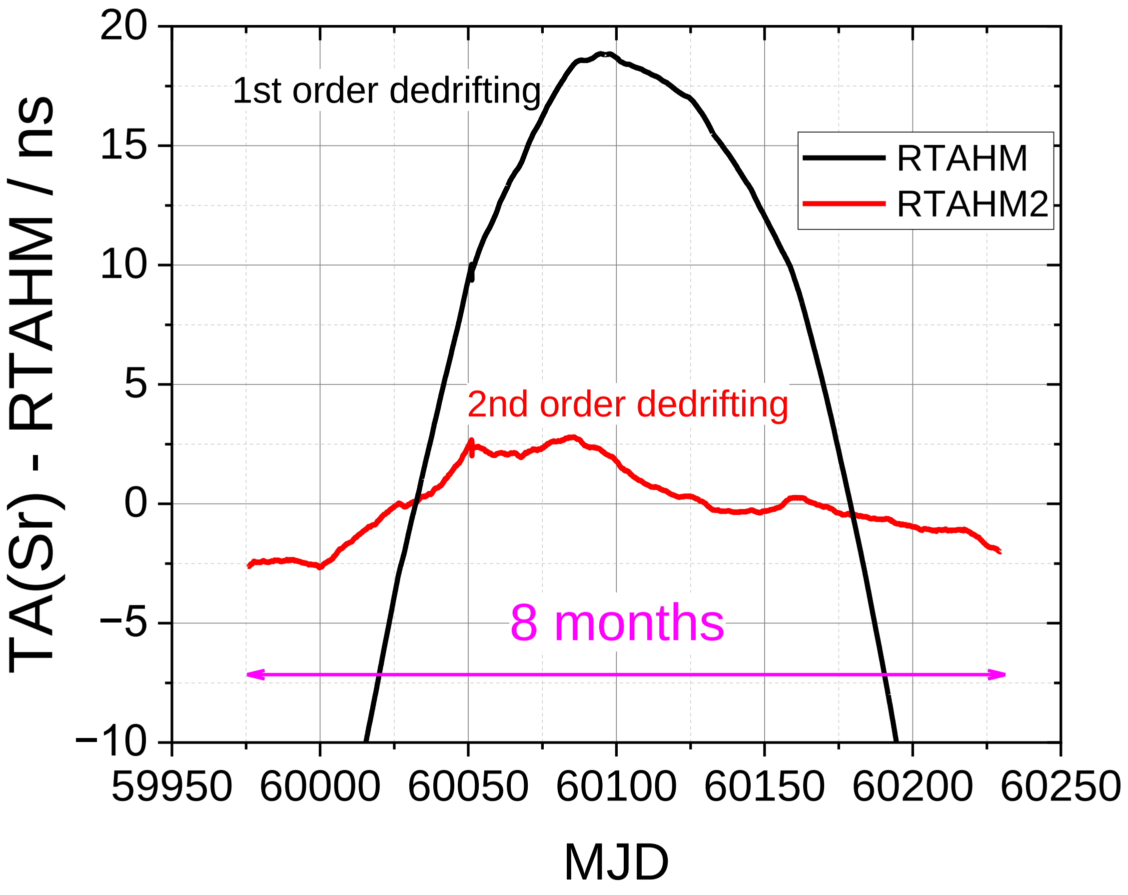
From Y. Hanado, IFCS-EFTF 2023 tutorial (2023)

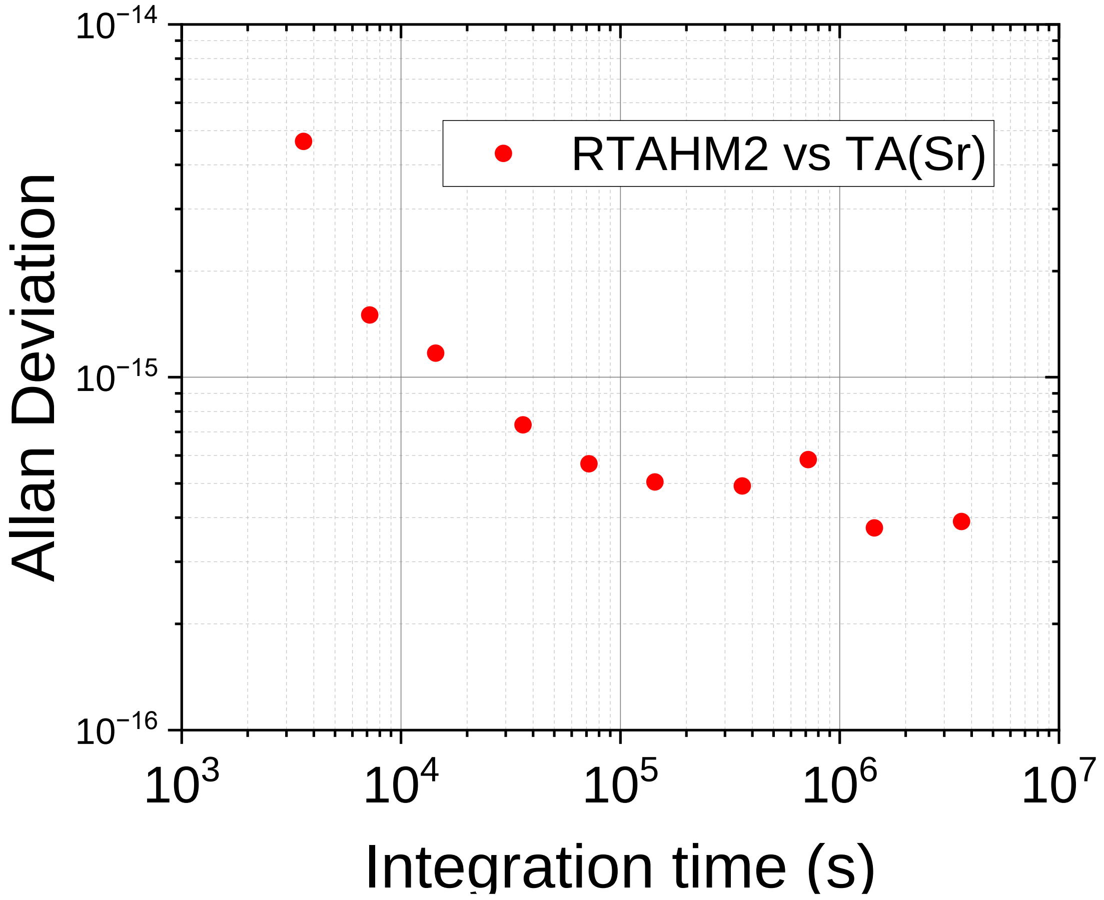
Consideration for independent timescale UTC(k)

- Reference for detrending
  - BIPM uses not EAL itself, but TT(BIPM) as the prediction reference
  - Local source is ideal for UTC(k), considering the resiliency
  - Independent signal, TA(Sr)? Or the ensemble timescale itself?

- Weighting
  - Allan deviation → Hadamard deviation

	BIPM (-2011)	BIPM (2011-)	UTC(NICT) (-2022)	UTC(NICT) (2023-)
Detrend (in phase)	linear	quadratic	linear	quadratic
Reference for prediction	EAL	TT	RTA	RTA@NICT
weight	Allan variance	predictability	Allan deviation	Hadamard deviation





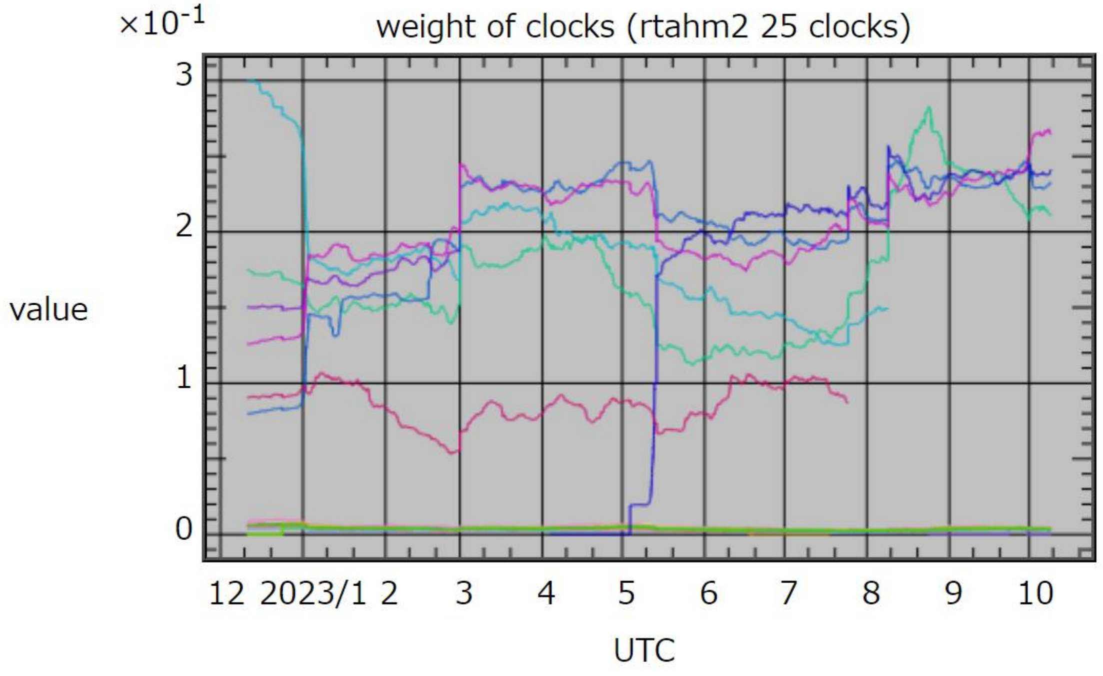
Similar level of stability with TA(Sr) up to one month

→ Steering using Circular T becomes an option

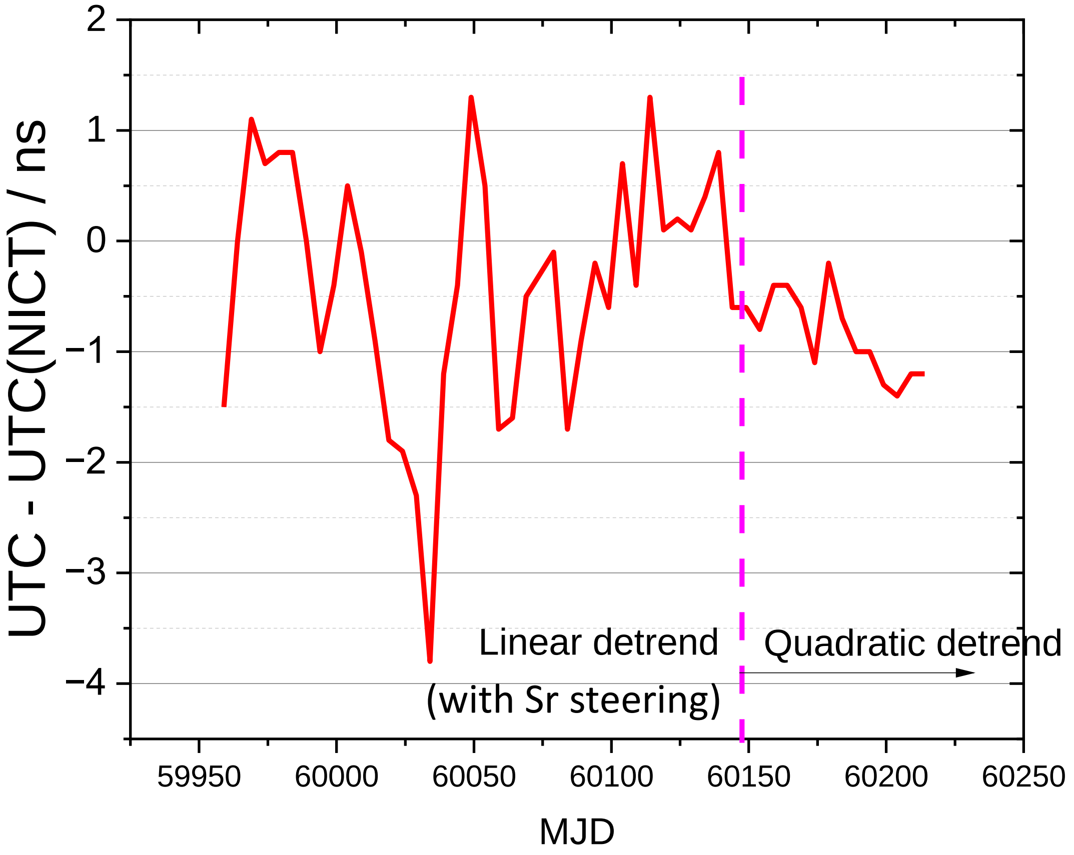
We need to provide (or adjust) three parameters.
Phase offset, frequency offset, frequency drift offset

Algorithm to incorporate Sr data will be explored.

Improvement after quadratic detrending



4 or 5 stable HM has weight in similar level.



Next step & outlook

- Optimization of TA(HM)
  - Reference for dedrifting
  - weight

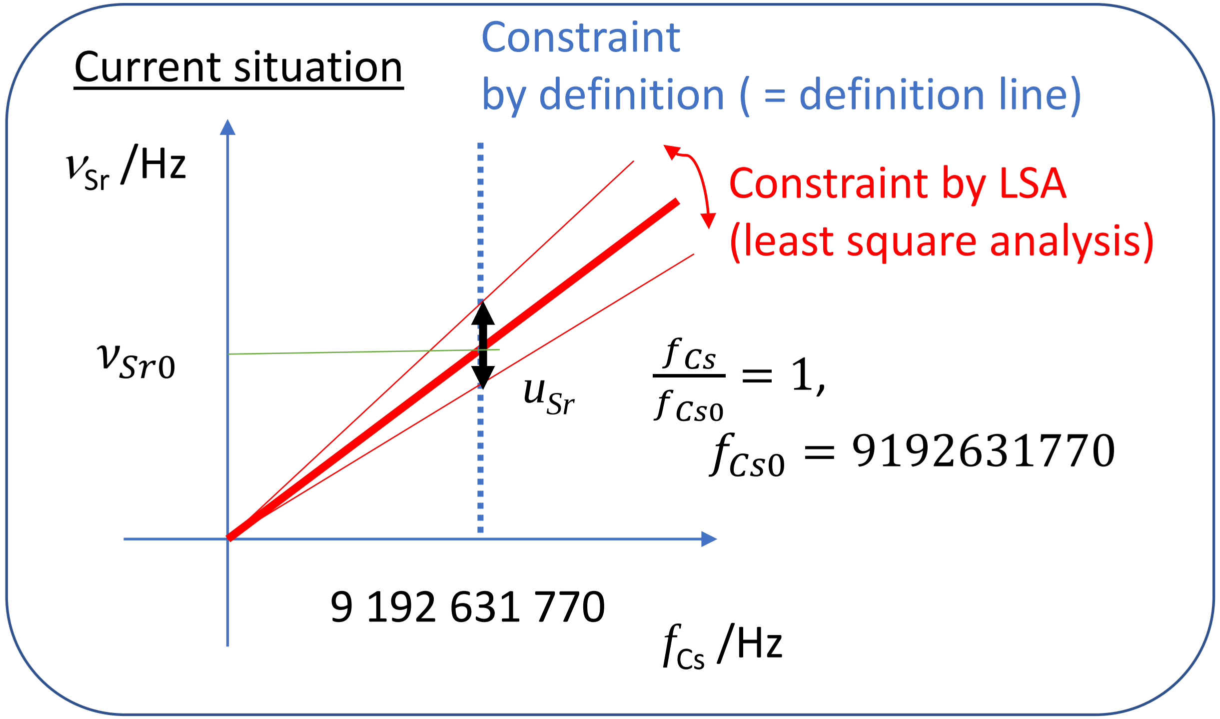
- Adjusting three parameters (phase, frequency, frequency drift) based on intermittent operation of the optical clock and Circular T for phase alignment
  - Kalman filter which can manage both frequency and phase data?

(Poster No. 112)

- Second or possibly commercial lattice clocks
  - Redundancy for public service could be achieved by commercial system (For instance, Poster No. 82 by Shimadzu)

Graphical picture of the option 1, 2a and 2b in the redefinition of the SI second

Choosing multiple transitions as primary transitions?



All measurements and least square analysis tell us that point (f_{Cs}, ν_{Sr}) falls on the red line with uncertainty.

"Definition" determines where the point is on the red line.

Currently, f_{Cs} is fixed to be 9192631770 Hz.

We find a intersection with the redline and vertical blue dot line.

The definition is **an ARTIFICIAL constraint to determine values.**

This constraint does not need to be vertical line, as long as it provides intersection with the red (LSA) line.

Further simplified picture

Option 1:

Definition LINE : ν_1=50
→Uncertainty only occurs in ν_2, ν_3, …

Another possibility: using arithmetic mean of two transitions

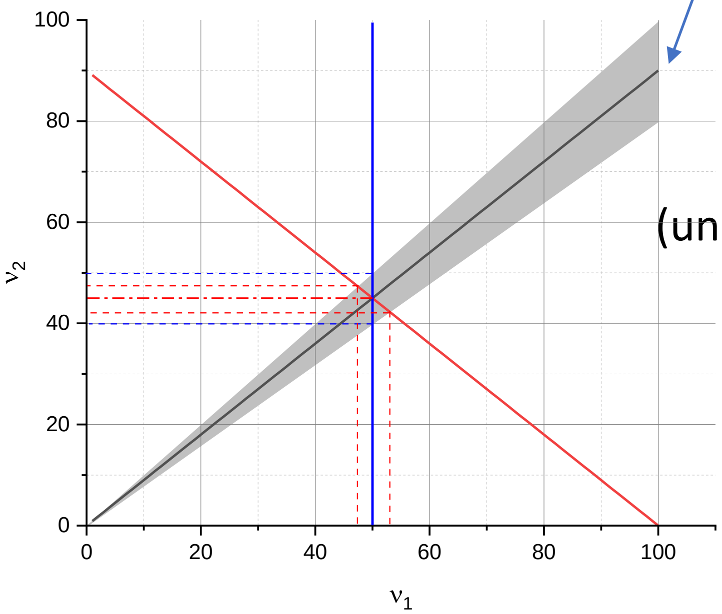
Definition LINE:

$$K\frac{\nu_1}{50}+(1-K)\frac{\nu_2}{45}=1 \qquad (1)$$

(note that $K=1 \rightarrow \nu_1=50$ (i.e. Definition1))

Option 1 (ν_1=50)

$\frac{\nu_2}{\nu_1}$ = 45/50=0.9(1)



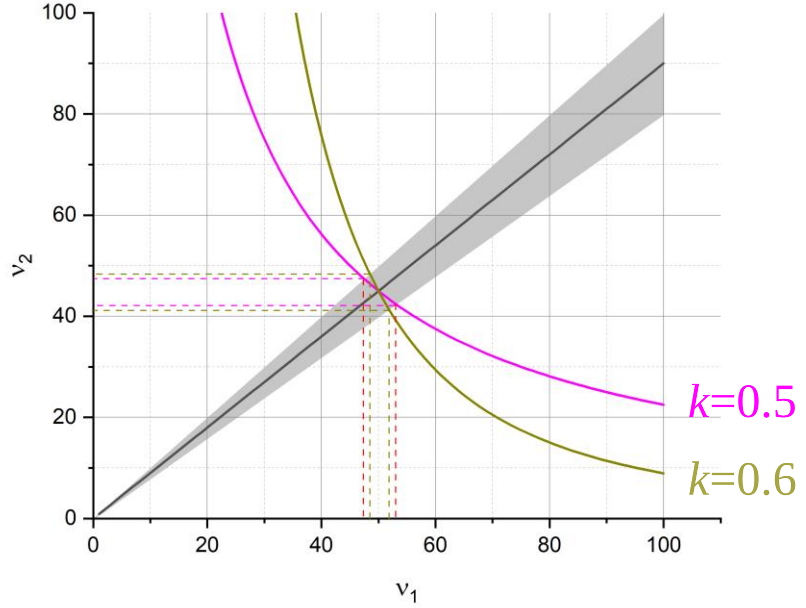
(uncertainty of the ratio 0.1)

$$\frac{\nu_1}{50}+\frac{\nu_2}{45}=2$$

If ν_1 and ν_2 has same uncertainty, it is fair to set the definition line as

$$\frac{1}{2}\frac{\nu_1}{50}+\frac{1}{2}\frac{\nu_2}{45}=1 \rightarrow \frac{\nu_1}{100}+\frac{\nu_2}{90}=1$$

Weight & nominal frequencies are mixed, and we cannot separate them…



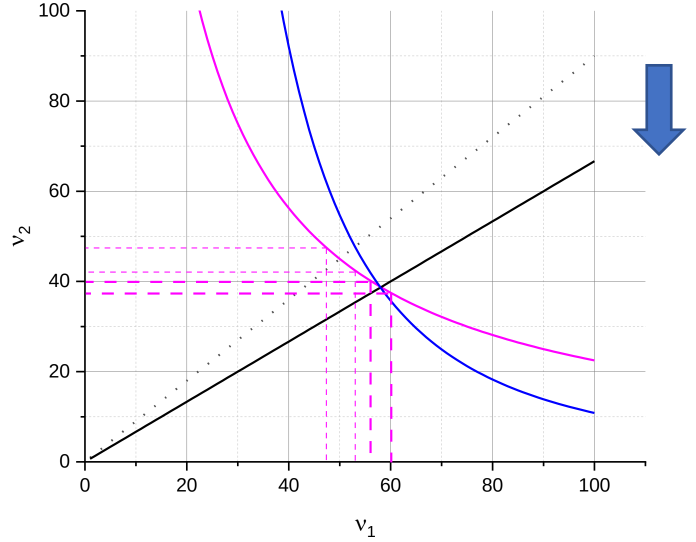
Definition line can also be a curve.

Indeed, curves that “Geometric mean = constant” is curve

$$\nu_1^k \nu_2^{1-k} = 50^k 45^{1-k} (= N)$$

This formula holds weights and nominal frequencies separately !

If weight is inversely proportional to the square of uncertainty, the projection of the confidence band to each axis determines the uncertainty of each transition frequency.



<u>Revision process</u>

New experiments shift black line and confidence band.

Option 2.a: the definition curve is not renewed.
(point stays on the original curve)

Option 2.b: the definition curve is renewed after (possibly choosing transitions), fix the intersection point, and finally setting weights

Summary

- Intermittent operation of an optical clock (once in a week) realized an optically steered timescale for two years.
- Ensemble of HMs with quadratic de-drifting has good stability. We need a recipe to determine the offset paremeters in phase, frequency, and frequency drift.
- Option 2 in the redefinition of the SI second does not bring you to a totally different regime. Option 1 could have been just a special case of option 2.

Teams

Members of the space-time standards laboratory, including those for telecom-related T&F research, public service, and technical & administrative support

Lattice clock M. Tonnes

In the audience: **N. Nemitz** **H. Hachisu**

T&F comparison

T. Gotoh
Y. Kozuki
R. Ichikawa

H. Ito K. Matsubara N. Ohtsubo Y. Miyauchi M. Morikawa

Generation of Japan Standard Time