# UTC(NICT) Referenced to a Timescale Based on the Optical Clock NICT-Sr1

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***Since August 2021, Japan Standard Time is generated at NICT with reference to the strontium optical lattice clock NICT-Sr1, and the deviation of the underlying local realization UTC(NICT) from UTC has been reduced to few nanoseconds.***

***Keywords—timescale, UTC(k), optical clock, optical lattice clock, intermittent measurement***

## I. INTRODUCTION

Precise, reliable time information is a key infrastructure for modern communications technology. The local realizations of the Coordinated Universal Time UTC($k$) generated at institute $k$ currently rely on microwave atomic clocks to pre-empt and implement the retro-actively calculated Coordinated Universal Time UTC as accurately as possible.

The National Institute of Information and Communications Technology (NICT) generates and provides UTC(NICT), from which Japan Standard Time JST is derived by adding +9 hours. This time is disseminated throughout Japan in various ways. In the last 15 years, the deviation of UTC(NICT) from UTC has been kept within ±25 ns.

Minimizing this deviation is not the only goal, however. NICT relies on the global navigational satellite networks for its time links to UTC, a dependency that is recently considered with increasing concern [1]. It is desirable to make UTC(NICT) robust and able to operate for an extended time without adjustments, which requires a very good reference clock. Other institutes like PTB, USNO, and LNE-SYRTE began using continuously operated cesium or rubidium fountain clocks for this purpose a number of years ago [2–4]. In a slightly different approach, NICT has been one of the first institutes to push for an optical clock to steer the nationally distributed timescale [5].

Optical atomic clocks have seen dramatic development over the last decades and surpass fountain clocks in terms of both stability and accuracy, which makes them an obvious avenue for improved timescale implementations. Previous work [5–8] has reported on 'paper' timescales created by post-processing the data of a hydrogen maser (H-maser) source oscillator according to optical clock measurements. In the same way, an all-optical timescale with a laser stabilized to a silicon cavity acting as source oscillator has been explored [9]. A European project targeting an international timescale based on optical atomic clocks [10] has demonstrated operation of such clock with much improved operating times.

Demonstrating the capability of optical atomic clocks to contribute to timescale generation is one of the criteria set by the Consultative Committee for Time and Frequency CCTF for the redefinition of the SI second from the current microwave transition in cesium to one or more optical transitions.

In 2016, NICT was the first institute to generate an internal real-time timescale signal based on an optical atomic clock [11].

Here we report on the first application of such an optically steered timescale in the generation of nationally distributed time, and the resulting improvement in the performance of Japan Standard Time since August 2021.

## II. METHODS/RESULTS

Fig. 1 shows the configuration of UTC(NICT) referenced to the optically steered timescale TA(Sr). The generation of this independent timescale based on a H-maser source oscillator steered using the $^{87}$Sr optical lattice clock NICT-Sr1 [11] was resumed in July 2021. NICT-Sr1 intermittently operates for

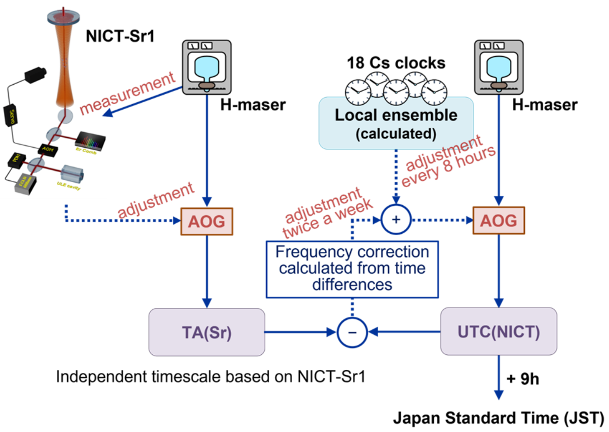


Fig. 1. Configuration of the generation of UTC(NICT) referenced to a optically steered timescale TA(Sr) based on NICT-Sr1. Conventionally generated UTC(NICT) is adjusted by frequency difference between TA(Sr) and UTC(NICT) towards TA(Sr) twice a week. This does not harm the traditional system and can be easily reverted to the previous configuration. AOG is an auxiliary output generator. Solid lines show time and frequency signals, dashed lines are calculated values.

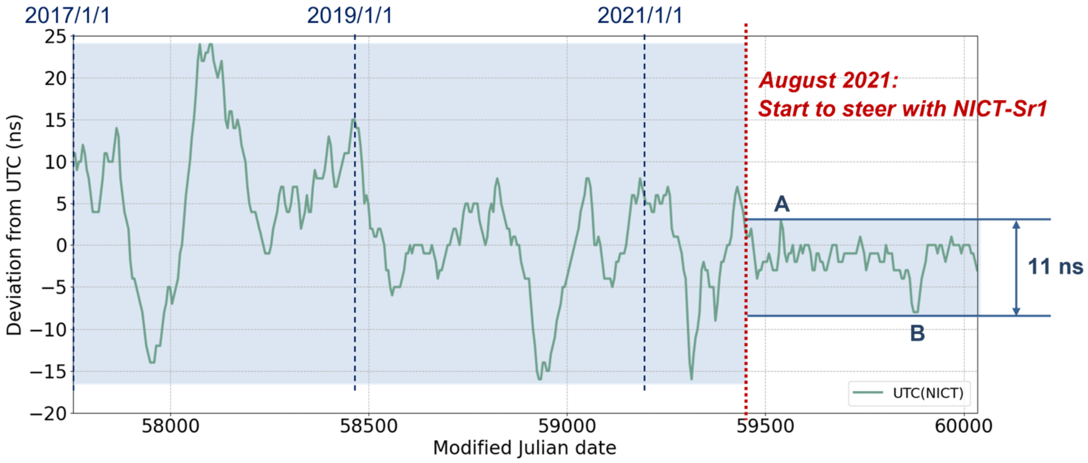


Fig. 2. Time difference UTC − UTC(NICT) since 2017. UTC(NICT) is adjusted to the optically steered timescale TA(Sr) twice a week since August 2021.

usually three to seven hours once per week and each operation yields a datapoint for the H-maser frequency that is stored in a database. An automatic evaluation of the data is executed once per hour to model the evolution of the H-maser frequency in terms of a linear drift over an interval [12, 13] of typically 30 days. The frequency correction applied to the H-maser signal by a phase micro-stepper (alternatively referred to as auxiliary offset generator, AOG) is also updated at this time.

UTC(NICT) is similarly implemented as a H-maser signal frequency-adjusted by AOG, although these systems exist in triplicate for redundancy. Previously, the frequency adjustment has been based on a calculated local ensemble time, determined from a maximum of eighteen commercial cesium atomic clocks [14]. Additional corrections were manually included only when the time difference |UTC − UTC(NICT)| may exceed 20 ns.

Adding steering by NICT-Sr1 further decreases the reliance of UTC(NICT) on international frequency links. To maintain robustness, the optical clock is incorporated by a loose coupling to TA(Sr): This is realized by adjusting the frequency of UTC(NICT) twice per week by the difference $y$(UTC(NICT) − TA(Sr)). This frequency difference is determined from hourly time differences collected over 24 hours. As currently implemented, an additional, smaller frequency correction is added to compensate the time difference between UTC(NICT) and TA(Sr) over 60 days. The adjustments were started in August 2021 and now continue for close to two years.

NICT-Sr1 has been recognized as a secondary frequency standard, and we use the frequency recommended by the International Committee for Weights and Measures CIPM to evaluate its measurements. We nevertheless encounter a timing drift of TA(Sr) relative to UTC approximately corresponding to a previously measured frequency difference of less than $2 \times 10^{-16}$ [15] between the absolute frequency of NICT-Sr1 and the CIPM recommended frequency. All calculations performed to couple UTC(NICT) to TA(Sr) include an adjustable correction for this frequency difference to avoid a resulting timing drift of UTC(NICT) relative to UTC.

Fig. 2 shows the deviation of UTC(NICT) from UTC since 2017, as reported in the Circular T. Before the start of adjustment to TA(Sr) in August 2021, the deviation of UTC(NICT) is typically ±25 ns. Afterwards, the deviation is reduced to typically 3 ns or less, with the exception of two relatively large excursions. The first (“A”) is due to an approximately +6 ns timing step caused by switching UTC(NICT) to another of the three redundant candidate implementations. The second (“B”) resulted from the failure of a mechanical shutter in NICT-Sr1, which caused the atoms to be exposed to leaked cooling light at a wavelength of 689 nm. The resulting frequency shift was discovered and compensated for based on the observed timing drift of TA(Sr) relative to the rapid realization UTCr. Once the cause had been identified, interleaved measurements of NICT-Sr1 confirmed a systematic frequency shift on the level of a few $10^{-15}$, consistent with the applied correction. The loosely coupled steering provided an opportunity to correct for the erroneous measurements and avoided the accumulation of a larger time difference.

## III. Conclusions

For close to two years, NICT has now generated JST and the underlying UTC(NICT) signal adjusted to the independently generated optically steered timescale TA(Sr). To the best of our knowledge, this is the first time that an optical clock has been incorporated in the generation of a nationwide disseminated timescale. The improved steering has reduced the deviations of UTC(NICT) from UTC by a factor of three to four. Further reduction of the deviation is expected by improving the reliability of the optical clock and its measurement system. The inclusion of the optical clock as a precise local reference improves the resilience of UTC(NICT) during an interruption of the international time links based on the global navigational satellite networks, while the deliberately loose coupling to TA(Sr) avoids introducing a new single-point-of-failure and thus maintains the robustness of the timescale.

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